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Journal

of

THE ROYAL AERONAUTICAL SOCIETY

MARCH 1958

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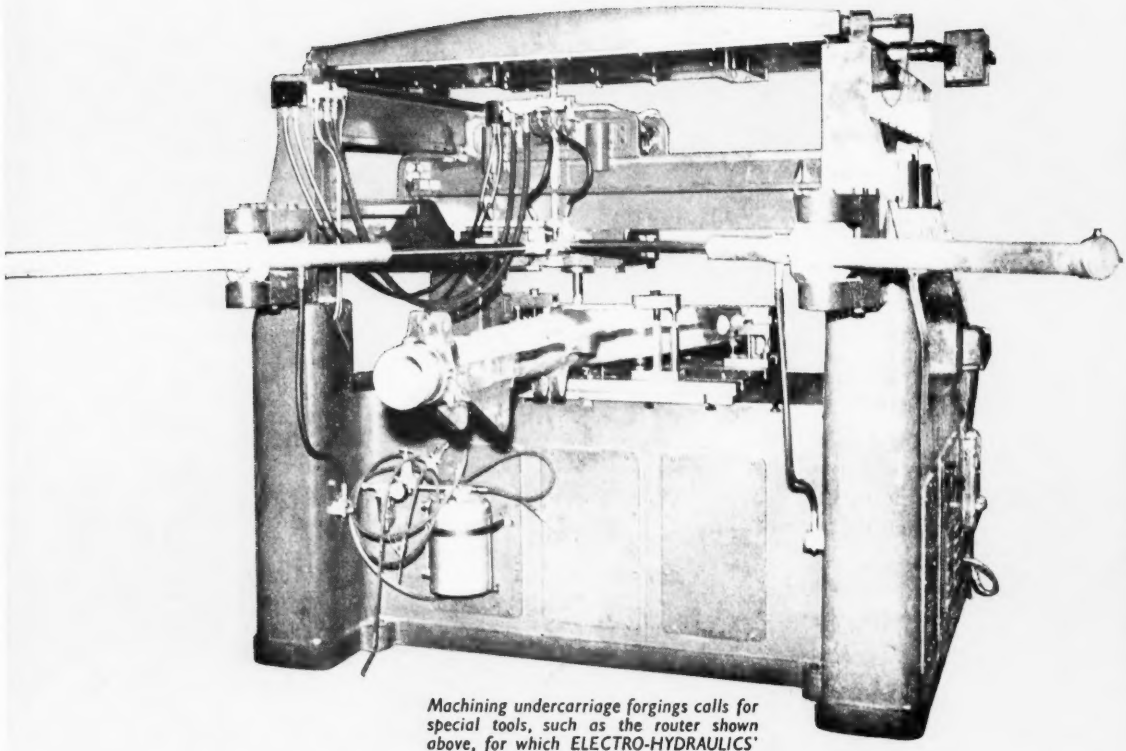

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Journal of

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ADDITIONS TO THE LIBRARY. REPORTS.

All communications for publication in, and advertisements for, the JOURNAL *should be addressed to the Editor,* JOAN BRADBROOKE, *A.R.Ae.S.; all communications on general matters affecting the Society should be addressed to the Secretary,* A. M. BALLANTYNE, *T.D., B.Sc., Ph.D., Hon.F.C.A.I., A.F.I.A.S., F.R.Ae.S.*

None of the papers or paragraphs must be taken as expressing the opinion of the Council of the Royal Aeronautical Society unless otherwise stated.

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(Founded 1866)

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NOTICES

Annual General Meeting—8th May 1958

NOTICE IS HEREBY GIVEN that the Annual General Meeting of the Royal Aeronautical Society, with which is incorporated the Institution of Aeronautical Engineers, will be held on Thursday 8th May at 5.30 p.m. in the Offices of the Society, 4 Hamilton Place, London, W.1.

AGENDA

1. To read the Notice convening the Meeting.
2. To receive and deliberate upon the Report of the Council on the state of the Society and the Balance Sheet and Income and Expenditure Accounts of the Royal Aeronautical Society and Aeronautical Trusts Limited for the year ended 31st December 1957.
3. To receive the names of those elected to Council for the years 1958-1961.
4. To announce the names of Fellows elected by the Council in accordance with By-Law 4.
5. To elect the Auditors for the year 1958.
6. Any other business.

By Order of the Council,
A. M. BALLANTYNE,
Secretary.

NOTE: In accordance with the By-Laws any member whose subscription has not been paid before the first day of April is not entitled to vote.

Light refreshments will be served after the meeting.

Nominations of Candidates for Council

The following is an extract from the By-Laws:—

"The Twenty-one ordinary members (of the Council) shall be nominated and elected from among the members of the Society. At the date of their election at least ten shall be Fellows, and one at least shall be in each of the following classes: Associate Fellow, Associate and Graduate.

"Of the ordinary members of the Council, that number necessary to create seven vacancies shall retire annually. The retiring members shall be those with the longest service since their last election but they shall be eligible for re-election.

"Nominations of candidates for election to the Council must be received by the Secretary not later than 10th April in each year and shall include statements in writing by the candidates that they are willing to serve. The nomination forms shall be signed by one proposer and two seconders, all of whom shall be Voters."

Nomination forms may be obtained on application to the Secretary.

Air Transport Course 1958—Oxford

23rd March–3rd April. 8th April–12th April

The Third Air Transport Course will be held at Oriel College, Oxford, from the 23rd March to the 3rd April, with a break for the Easter week-end 4th, 5th, 6th and 7th April. The Course will re-assemble on Monday evening 7th April, then continue from the 8th April to the 12th. Full particulars may be obtained on application to the Secretary of the Society. The Course will follow the lines of previous courses with lectures on Operations, Air Law and Economics and there will again be a number of guest lecturers.

Institute of Metals Symposium

The Metallurgical Engineering Committee of the Institute of Metals are holding an all-day Symposium at Church House, Westminster, at 9.30 a.m., on 1st May 1958 on "Advances in Inspection Techniques as Aids to Process Control in Non-Ferrous Metals Production." Admission tickets are not required and members of the Society are invited to attend.

British Commonwealth Lecture

The Thirteenth British Commonwealth Lecture, "Why Airlines are Hard to Please," will be given by Mr. B. S. Shenstone, M.A.Sc., F.C.A.I., A.F.I.A.S., F.R.Ae.S., on 27th March 1958 at the Institution of Civil Engineers, Great George Street, S.W.1, at 6.0 p.m. Tea will be served at 5.30 p.m.

Royal Aeronautical Society Prize for Henlow Cadets

The Council, at a recent Meeting, agreed to establish a Royal Aeronautical Society Prize for the Cadet, at R.A.F., Henlow, who obtains the best aggregate of marks in the final year Higher National Diploma assessed examination subjects. The Prize takes the form of Graduate Membership of the Society for three years without payment of subscriptions. In addition, a book is presented to the successful Cadet to commemorate the award.

The first award of the Prize has recently been made to Pilot Officer M. S. Malpass.

AGARD Meetings—A Correction

In the February Notices it was incorrectly stated that the Combustion and Propulsion Panel of A.G.A.R.D. would hold its Third Colloquium in Rome from 17th to 21st March. This meeting will be held in **Palermo, Sicily,** as originally arranged. It is the Seventh Meeting of the Structures and Materials Panel which is now meeting in Rome (from 24th March to 2nd April).

Mond Nickel Fellowships

Applications are invited for the 1958 Mond Nickel Fellowships of approximately £900 to £1,200. The Fellowships will be awarded to candidates of British nationality with degree or equivalent qualifications, for additional training in industrial establishments, at home or abroad, to make them more suitable for employment in senior technical and administrative positions in British Metallurgical Industries.

Particulars and application forms (which must be returned by 1st June 1958) are obtainable from:—The Secretary, Mond Nickel Fellowships' Committee, 4 Grosvenor Gardens, S.W.1.

Annual Subscriptions

Members are reminded that their annual subscriptions became due on 1st January 1958. The rates are:—

	Home			Abroad		
	£	s.	d.	£	s.	d.
Fellows	5	5	0	4	4	0
Associate Fellows	4	4	0	3	3	0
*Associates	3	3	0	3	3	0
Graduates (aged under 26)	2	2	0	2	2	0
Graduates (aged 26 and over)	2	12	6	2	12	6
Students (aged under 21)	1	1	0	1	1	0
Students (aged 21 and over)	1	11	6	1	11	6
Companions	3	3	0	3	3	0
Founder Members	2	2	0	2	2	0

* Any Associate elected before 1st October 1947 may, if he wishes, elect not to receive the Journal, and in this case his subscription will be reduced by £1 1s. 0d. to £2 2s. 0d.

It will avoid delay and confusion if members, when sending remittances for subscriptions, will state their names clearly and give their addresses and grades of membership. Remittances should be made payable to the Royal Aeronautical Society.

Extract from By-Law 18. Any member whose subscription has not been paid before **the first day of April** shall be in arrears of subscription and shall be notified that he is not entitled to attend or vote at any meeting or to receive any publications.

DIARY

LONDON

13th March

MAIN LECTURE AT CHRISTCHURCH BRANCH.—Flight Tests of a Meteor Aeroplane fitted with Jet Deflection. P. F. Ashwood and D. Lean. Bournemouth Municipal College, Lansdowne. 7.30 p.m.

27th March

THE THIRTEENTH BRITISH COMMONWEALTH LECTURE.—Why Airlines are Hard to Please. B. S. Shenstone. Institution of Civil Engineers, Great George Street, S.W.1. 6 p.m. (Tea at 5.30 p.m.)

10th April

MAIN LECTURE.—Guided Weapons. Dr. R. Cockburn. Institution of Mechanical Engineers, Birdcage Walk, S.W.1. 6 p.m. (Tea at 5.30 p.m.)

15th April

SECTION LECTURE.—The Problems of Vertical Take-Off. Dr. C. T. Hewson. Library, 4 Hamilton Place, W.1. 7 p.m.

GUIDED FLIGHT SECTION

20th March

Problems in the Development of a Guided Missile. J. Clemow. Royal Institution, 7 Albemarle Street, W.1. 6 p.m.

GRADUATES' AND STUDENTS' SECTION

25th March

Annual General Meeting followed by Film Show. 4 Hamilton Place, W.1. 7.30 p.m. (Light refreshments 7 p.m.)

BRANCHES

11th March

Boscombe Down.—Navigation and the Air Traffic Control Problem. D. O. Fraser. Lecture Hall, A. and A.E.E. 5.45 p.m.

Glasgow.—Next Generation of Civil Aircraft. G. H. Lee. Room 24, College of Science and Technology, Duke Street, Glasgow. 7.15 p.m.

12th March

Chester.—The Investigation of Aircraft Accidents. E. L. Ripley. Lecture Theatre, Grosvenor Museum, Chester. 7.30 p.m.

Gloucester.—Problems of the Large Helicopter. Dr. G. S. Hislop. The Wheatstone Hall, Brunswick Road, Gloucester. 7.30 p.m.

Southampton.—Future Developments with Satellite Rockets. L. R. Shepherd. Institute of Education, University of Southampton. 7 p.m.

Swindon.—Annual General Meeting and "Viscount" films. The College, Victoria Road, Swindon. 7 p.m.

Weybridge.—Aircraft Production; Present and Future. Joint meeting with the Institute of Mechanical Engineers. S. P. Woodley. Apprentice Training School, Weybridge. 6 p.m.

13th March

Christchurch.—MAIN SOCIETY LECTURE. Flight Tests of a Meteor Aeroplane fitted with Jet Deflection. P. F. Ashwood and D. Lean. Bournemouth Municipal College, Lansdowne, 7.30 p.m.

17th March

Bristol.—BARNWELL MEMORIAL LECTURE. The Economy of Structures. Sir Alfred Pugsley. Bristol University Engineering Lecture Theatre, 7 p.m.

Henlow.—Film Evening. Building 62, R.A.F. Technical College. 7.30 p.m.

19th March

Leicester.—Aircraft Photography 1913-1957. John Yoxall. Lecture Theatre, Loughborough College. 6.45 p.m.

20th March

Cambridge.—The Pioneers. N. J. Capper. No. 1 Lecture Theatre, Cambridge University Engineering Laboratories. 8.15 p.m.

Isle of Wight.—The Development of Power Plants for Supersonic Flight. Dr. E. S. Moult. J. Edwards and W. Neat. Clubhouse, Saunders-Roe Sports and Social Club, E. Cowes. 6.30 p.m.

Yeovil.—A Review of Private Flying. A. Elsmore. Park School, Park Road. 7.30 p.m.

21st March

Birmingham.—A Talk on Astronomy. M. W. Ovenden. Engineering Centre, Birmingham. 7.30 p.m.

25th March

Luton.—Annual General Meeting and Presidential Address. Napier Senior Staff Canteen, Luton Airport. 6.15 p.m.

26th March

Hatfield.—Civil Airworthiness and the Air Registration Board. R. E. Hardingham. de Havilland Restaurant. 6.15 p.m.

Preston.—American Production Methods. A. W. Turner. Queen's Hotel, Lytham. 7.30 p.m.

27th March

Bristol.—Annual General Meeting and Film Show. Filton House. 6 p.m.

Glasgow.—Application of Electronic Control Techniques to Aircraft. Member of Staff of Ferranti Ltd., Edinburgh. Room 24, College of Science and Technology, Duke Street, Glasgow. 7.15 p.m.

1st April

Boscombe Down.—Aircraft Accident Investigation. E. L. Ripley. Lecture Hall, A. and A.E.E. 5.45 p.m.

Luton.—Arctic and Tropical Trials. R. K. Cushing. Napier Senior Staff Canteen, Luton Airport. 6.15 p.m.

2nd April

Brough.—The Beverley in Service. Gp. Cpt. F. C. Griffiths. Lecture Hall, Electricity Offices, Ferensway, Hull. 7.30 p.m.

Christchurch.—Casting Light Alloys. Mr. Eade. Kings Arms Hotel. 7.30 p.m.

Weybridge.—The Future of Nuclear Propulsion. Rear-Admiral Sir Edward Rebbeck, J. C. L. Puxley and Capt. H. Farquhar-Atkins. Apprentice Training School. 6 p.m.

3rd April

Isle of Wight.—Contour Etching. A. W. Sheppard. Clubhouse, Saunders-Roe Sports and Social Club, E. Cowes. 6.30 p.m.

Reading.—Brains Trust. Upper Canteen, Western Manufacturing (Reading) Ltd. 6 p.m.

7th April

Derby.—The Tyne Turbo-Propeller Engine. D. McLean. Rolls-Royce Welfare Hall, Nightingale Road. 6.15 p.m.

9th April

Chester.—Air-to-Air Photography. Russell Adams. Lecture Theatre, Grosvenor Museum. 7.30 p.m.

Glasgow.—Annual General Meeting and Film Show. Room 24, College of Science and Technology, Duke Street. 7.15 p.m.

Swindon.—The History of the Supermarine Works of Vickers-Armstrongs (Aircraft) Ltd. A. N. Clifton. The College, Victoria Road. 7 p.m.

10th April

Cheltenham.—Annual General Meeting and Film Show. St. Mary's College, Cheltenham. 7.30 p.m.

Yeovil.—Annual General Meeting and Film Show. Park School, Park Road. 7.30 p.m.

11th April

Hatfield.—Annual Dinner.

14th April

Halton.—Aircraft Photography. John Yoxall. Branch Hut, R.A.F. Halton. 6.45 p.m.

16th April

Brough.—Annual General Meeting. Lecture Room, Flying Club, Brough. 5.10 p.m.

Christchurch.—Joint meeting with the Institution of Mechanical Engineers. Lecture by G. W. H. Gardner. Town Hall. 7.30 p.m.

London Airport.—Titanium. H. W. Shaw. Apprentice Lecture Room, Fairey Aviation Co. Ltd., Hayes. 6 p.m.

Preston.—Annual General Meeting and Film Show. R.A.F. Association, Preston. 7.30 p.m.

18th April

Birmingham.—Reduxed Aircraft Structures. Engineering Centre, Birmingham. 7.30 p.m.

21st April

Halton.—Film Night and Committee Meeting. Branch Hut, R.A.F. Halton. 6.45 p.m.

23rd April

Christchurch.—Annual General Meeting and Film Show. Kings Arms Hotel. 7.30 p.m.

Hatfield.—Discussion Evening. de Havilland Restaurant. 6.15 p.m.

Leicester.—Annual General Meeting and Film Show. Lecture Theatre, Loughborough College. 6.45 p.m.

30th April

Reading.—Annual General Meeting and Film Show. Upper Canteen, Western Manufacturing (Reading) Ltd. 6 p.m.

Weybridge.—Annual General Meeting. Apprentice Training School. Weybridge. 6 p.m.

News of Members

R. Brown (*Associate Fellow*), formerly at Lucas-Rotax (Toronto) Ltd., has joined the General Electric Co.—Small Aero Engine Department, Lynn, Mass.

Wing Commander R. Brown (*Associate Fellow*), formerly of H.Q. Bomber Command, has been appointed Officer Commanding, Bomber Command, Armament School, High Wycombe.

D. S. Carton (*Associate Fellow*), formerly a Demonstrator at the College of Aeronautics, Cranfield, has been appointed Lecturer in the Department of Aircraft Propulsion.

Dr. W. Cawood (*Associate Fellow*), formerly P.D. Scientific Research (Air), is now Deputy Controller (Air) Research and Development, Ministry of Supply.

W. Davis (*Associate Fellow*), formerly with the Plessey Co. Ltd., is now Sales Manager of Western Manufacturing (Reading) Ltd.

Wing Commander T. U. Dunn (*Associate Fellow*), formerly at R.A.F. Station, Upavon, has been posted to H.Q. Middle East Air Force, R.A.F., Episkopi, Cyprus.

D. Ellington (*Graduate*), formerly at Fairey Aviation Co. Ltd., is now an Aerodynamicist with Canadair Ltd. in the Special Weapons Engineering Division.

W. P. Escreet (*Companion*), formerly with the de Havilland Engine Co. Ltd., has been appointed Lecturer in Mechanical Engineering at Northampton College of Advanced Technology.

E. T. Jones (*Fellow*), formerly Director General of Technical Development (Air), is now the Deputy Controller of Overseas Affairs, Ministry of Supply.

J. Ling (*Graduate*), formerly with Hawker Aircraft Ltd., is now a Design Engineer with the Iraq Petroleum Co. Ltd. and Associated Companies, Persian Gulf.

D. G. Maskrey (*Associate*) has been appointed Executive Mechanical Design Engineer, Ultra Electric Ltd.

W. McKim (*Associate Fellow*), formerly with the M.O.S., Bishopton, has been appointed a technical officer Grade 5, with the Canadian Defence Research Board, New Quebec City.

R. D. Mills (*Graduate*), formerly at Imperial College, has been appointed Fluid Mechanics Lecturer at the Royal College of Science and Technology, Glasgow.

D. Portas (*Associate*), formerly with Electra Methods Ltd., Stevenage, is now a Senior Development Engineer with Motor and Electronic Corporation Laboratories, Hertfordshire.

A. B. Pippet (*Associate Fellow*), formerly at Rose, Downs and Thompson Ltd., is now with F. W. Berk and Co. Ltd., Stratford.

M. Randrup (*Associate*) has been awarded, jointly with Mr. Walter Shirley, the Britannia Trophy by the Royal Aero Club. The Trophy has been awarded for the World Aeroplane Height Record of 70,310 ft. in an English Electric Canberra at Luton Aerodrome on the 28th August 1957.

R. Sewell (*Student*), formerly at Brockworth Engineering Co. Ltd., is now Production Manager with Expert Heat Treatments Ltd., Morden.

G. M. Silvester (*Associate Fellow*), formerly with Auster Aircraft Ltd., is now a Design Engineer at Boeing Airplane Co., Washington (Transport Division).

Squadron Leader J. P. Spillane (*Associate Fellow*), formerly of the Ministry of Supply, R.A.E., Westcott, has joined the Directorate of G.W., Air Ministry, London.

J. A. C. Williams (*Associate Fellow*), formerly Head of Engineering Training Method Study Dept., National Coal Board, has been appointed Principal of the College of Aeronautical and Automobile Engineering, Chelsea.

C. V. Wills (*Associate*), formerly an Experimental Officer with the Ministry of Supply at Boscombe Down, is now with the Air Registration Board as a Power Plant Surveyor.

Elections

The following is a list of new members and transfers of membership of the Society:—

Associate Fellows

Harold Rutherford Alexander
John Henry Allen (*from Student*)
Bernard George Ambrose (*from Graduate*)
Shankerlal Dayljibhai Amin (*from Associate*)
John David Arthur (*from Graduate*)
Paul Badre
Antony Dobson Barber (*from Graduate*)
Francis Edgar Bartholmew (*from Graduate*)
Peter Philip Benstead (*from Associate*)
Charles Bradbury
Leonard John Bristow
Alan Henry Butler (*from Graduate*)
George Cairns
Roy Edward Champken (*from Graduate*)
Ian Clifford Cheeseman (*from Graduate*)
Peter Alfred Thomas Christopher (*from Graduate*)
Robert Alexander Cunningham
Harold Edward Curtis
James Peter Dainty (*from Graduate*)
Noel Daum
David Richard Dennis (*from Graduate*)
Geoffrey Bower Ducker (*from Graduate*)
Alan Howard Farrow (*from Graduate*)
Francis Leslie Freeman (*from Graduate*)
Graham Norman Galton (*from Graduate*)
Alan Geoffrey Rolfe Gilbert (*from Graduate*)
John Harold Grout (*from Graduate*)
Wilfred Henry Horton
Alfred William Ernest Houghton
James Michael Howe (*from Graduate*)
Antony Paul Kenyon
Henry Vernon King
Pughe Davies Lewis
David Omond MacDougall
Robert Angus MacKay (*from Graduate*)
John Mackereth (*from Graduate*)
Arthur William Frederick Metz (*from Associate*)
George Robert Moore
Terence Reginald Forbes Nonweiler
Leonard Eric Norton (*from Graduate*)
Leonard Kenneth Cyril Packham (*from Graduate*)
Frederick Arther Alfred Palmer (*from Graduate*)
George Pierce (*from Associate*)
John Maxwell Roberts (*from Graduate*)
William Francis Henry Crawford Rutherford
Sidney David Simpkin
John Trevor Stamper (*from Graduate*)
John Bartholomew Veal
Francis George Walker (*from Graduate*)
Peter Alan Lennox Watson (*from Graduate*)
Leonard Keith Whitting
Thomas Williams (*from Graduate*)
John William Wilson
Desmond John Yabsley (*from Graduate*)

Associates

William Tom Abbott
Leslie James Coates
Leslie Crowhurst
Montague Samuel Edmund Gumbley
Eric Handley
Claude John Lees
Peter Frederick Leigh-Mossley
Denis John Mottram
Herbert Arthur Singer
Wilhelm John Hamilton Sutherland

Graduates

George David Alford
Erik Amundsen
Mervyn Cyril Charles Bampton
Stanley Barrett (*from Student*)
John Stanley Bell
David John Blower
Edmund George Brown-Edwards
Reginald John Cant
Peter Beverley Caton
Charles Maclean Chester
John Deakin (*from Student*)
Hamid Farooq (*from Student*)
Joseph Fray
Anthony Gibbs (*from Student*)
Edward Dennis George Kemp (*from Student*)
Brian William Payne (*from Student*)
Keith Ridehalgh
Alan Rothwell (*from Student*)
Richard Treherne Slatter
Ian Michael Titchener
Derek John Woolley (*from Student*)

Students

Michael Edward Freeman Amey
Robert George Andrew Angel
Alan Keith Baker
Derek William Black
Malcolm John Bourbery
Eric Burbridge

John Raymond Calsacy
John Barry Sainsbury Carter
William Richard Chadwick
Roger Bryan Charlesworth
Robin Byrne Corbett
William John Dent
Prem Dutt
Antony John Evans
Roy Dennis Ford
David John Foster
John Gibbins
James Edward Grandage
David Anthony Griffiths
Edward John Harding
David William Haskett
Robert John Gustav Hitchens
Geoffrey Leonard Hooker
David Jeffrey Hopwood
John Humphreys
Charles Frank Johnson
Reginald Francis Lambert
Douglas Edward Lilley
David Hugh Lloyd
Terence McKenna
Paul Marlton
Jeffrey Charles Mole
Christopher Lucas Mollan
Jakis Neocleous
Antony John Newton
John Michael Orme
Michael Pavitt
Geoffrey John Pearce
Geoffrey George Robert Pudney
Brij Bhushan Sarna
Peter Rex Schofield
Norman Keith Smith
Michael Snook
John Charles Michael Thompson
Paul Thompson

Companions

Margaret Medwyn Macnee
Robert Bertram Eric Stubbs

Acknowledgment

The Council wishes to thank James H. Woodward, Esq. (*Associate*) for presenting a number of books and pamphlets to the Library.

Weekend School on "Flight"

A weekend school on "Flight" is to be held on Saturday and Sunday 22nd and 23rd March by King's College, University of Durham, at Newcastle. The fee will be 5s. A series of lectures tracing the evolution of aeronautics will be given by Mr. J. E. Allen, F.R.Ae.S., Head of Aerodynamics, Projects and Assessment Department, Weapons Research Division, A. V. Roe and Co. Ltd. Particulars may be obtained from the Director of Extra-Mural Studies, Joseph Cowen House, 153 Barras Bridge, Newcastle-upon-Tyne 1.

Conference on Noise

The British Occupational Hygiene Society will hold its Eighth Conference, which will deal particularly with Noise in Industry, in London on 1st April 1958 at 11.15 a.m. The conference is open to non-members of the British Occupational Hygiene Society on payment of a fee of one guinea. Further details can be obtained from the Hon. Scientific Secretary, Dr. D. Turner, The Associated Ethyl Company Ltd., Ellesmere Port, Cheshire.

Journal Binding—New Prices

The greatly increased postal rates, together with other rising costs, unfortunately necessitate revised charges for 1958 for the permanent binding of Journals. The increases will be 1s. 6d. on the 1957 volume and 2s. on previous volumes. The new charges will be:—

1957 Volume (including packing and postage *in the United Kingdom*) .. .. .. £1 4s. 0d.
Previous Volumes (including packing and postage *in the United Kingdom*) .. .. £1 6s. 0d.

Journals, with a note of the name and address of the sender, should be sent direct to The Lewes Press, Friars Walk, Lewes, Sussex, and the remittance to the Secretary at the Offices of the Society.

Members are asked to be certain that the address to which they want their Journals sent is the same on their letters to the Lewes Press and to the Society.

Self-Binder Cases

Self-Binder cases of the "Easibind" type to hold 12 Journals are available from the Offices of the Society at 11s. 6d. each.

Changes of Address or Appointment

To assist in keeping the records of members correct and up to date the Secretary will be glad if all members will notify him as soon as possible of changes of address. He would also like to know of any change of appointment.

When notifying changes please give the following particulars:—

Name (in block letters). Grade of Membership.
New address (in block letters). Old address.

New appointment.—Please give name and address of employer and position held.

Changes of address must be received *before the 15th of the month* in order to be effective for the Journal for the following month.

Russian Translations

The Secretary has been asked to draw the attention of members who speak Russian to the fact that The Pergamon Institute is engaged on a large scale translation programme from Russian aeronautical literature. They would be interested to hear from anyone who could assist with this programme on a part-time basis. Particulars may be obtained from the Administrative Secretary, The Pergamon Institute, 4 Fitzroy Square, London, W.1.

The Journal of the Royal Aeronautical Society

WITH WHICH IS INCORPORATED THE INSTITUTION OF AERONAUTICAL ENGINEERS

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Ram-Jets

by

R. P. PROBERT, M.A., A.F.R.Ae.S.

(Deputy Director, Engine Test Facilities, National Gas Turbine Establishment)

The 1055th Lecture to be given before the Society, "Ram-Jets" by R. P. Probert, was given on 12th December 1957 at the Institution of Mechanical Engineers, 1 Birdcage Walk, London, S.W.1. Dr. E. S. Moult, F.R.Ae.S., Vice-President of the Society presided. Opening the meeting Dr. Moult expressed the regrets of the President who was unable to be present. Introducing the Lecturer, Dr. Moult said that it was an event of some importance to have a paper on ram-jets and there was no one more qualified to give it than Mr. Probert. An Associate Fellow of the Society, Mr. Probert took his degree at Cambridge and spent a number of years at the Royal Aircraft Establishment and with Power Jets Ltd. After a period at the Johns Hopkins University in the United States of America, Mr. Probert joined the National Gas Turbine Establishment, Pyestock, in 1947, where he had been engaged continuously in research and development on gas turbines and ram-jets. More recently he had had a great part to play in the design and operation of the great test facility now nearing completion at Pyestock. It was a great work and much of the credit for it should go to Mr. Probert.

Introduction

The present time, when the prospect of high speed flight often seems to recede, not to approach, may well be a good occasion to review the ram-jet, an engine whose main use is at high flight speed. We owe the succinct name "ram-jet" to the Americans and the original idea to the French. But despite the admirable efforts abroad this paper is most concerned with British ideas, especially and naturally with those conceived and prosecuted at the National Gas Turbine Establishment. At the outset it is appropriate to acknowledge all the separate personal contributions to the subject of this paper and the assistance of my colleagues in preparing some of the information presented.

Avoiding painful delusions about flying stove pipes, the ram-jet consists of an intake or diffuser which converts to pressure some of the kinetic energy due to relative motion in flight and supplies the air inspired to a high pressure combustion chamber, which in turn discharges hot gas rearwards through a propelling nozzle. Pressure ratio naturally increases with flight speed, presuming appropriate aerodynamic design, and overall efficiency, or thrust work per unit of fuel, can increase indefinitely with speed towards 100 per cent. Practical limits are set either by excessive ram temperature introducing an alien cooling load in the normally cool part of the engine, or by inability to cool with hot ram air the normally hot parts of the engine at satisfactory flame temperatures. But these difficulties do not arise until a Mach number of 4 is exceeded and less conventional possibilities remain thereafter.

Ignoring effects of fuel mass and change of specific heat the ideal efficiency is simply

$$2 \times \frac{\text{Ram Temperature Rise}}{\text{Combustion Temperature Rise}} \times \times \left[\sqrt{\left(\frac{\text{Combustion Temperature}}{\text{Ram Temperature}} \right)} - 1 \right]$$

This expresses inevitably low efficiency at low speed and suggests very high efficiency at high speeds, especially when the combustion temperature rise is less than ram temperature rise. Fig. 1 defines the latent possibilities more exactly. Assuming complete expansion, efficiency and thrust per unit air flow at $M = 4{\cdot}0$ are plotted against combustion temperature rise for an engine with no losses, for another with good aerodynamics retaining 60 per cent total pressure at exhaust, and for a third retaining only 29 per cent. Overall efficiency does not vary sharply with aerodynamic efficiency in the practicable range, provided that the combustion temperature is suitably adjusted. With quite modest aerodynamic performance and modest combustion temperature, we can look for overall efficiencies of 50 to 60 per cent at $M = 4{\cdot}0$ with thrusts per lb. air flow equal to test bed values of the turbo-jet. This engine efficiency is roughly twice that of systems now propelling aircraft at speeds between $M = 0$ and $M = 1{\cdot}5$. The decline in efficiency at lower flight speeds is also shown.

There have been many attempts to use the ram-jet, often at a higher relative air speed than that of flight. For example, the Royal Aircraft Establishment quite

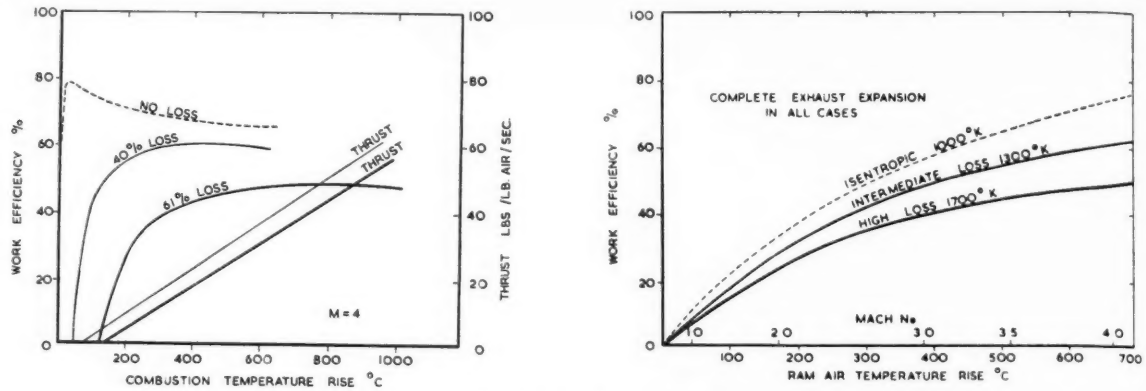


FIGURE 1. Simplified performance trends.

early tried driving a propeller with tip ram-jets and this has a modern counterpart in the ram-jet tip drive of helicopters, but with subsonic tip speeds the equivalent brake horsepower can only be obtained at 5 to 10 per cent efficiency, and such schemes depend upon the low weight of a simple engine giving relief from heavy fuel consumption for short endurance. During the 1939-45 War German invention was very active. Some serious, although inconclusive, work was done on subsonic engines leading to trials in lorry dashes down an autobahn and, more usefully, on a Dornier. Another idea was the simplest possible ram-jet with a solid fuel bed to shove a missile at supersonic speeds. But solid fuels have low calorific value and the quantity stored in a combustible arrangement within the duct is limited and thrust control is obviously restricted. A better idea perhaps was to increase the range of a gun-fired shell by building a small ram-jet around it and using ram pressure to expel a small liquid fuel charge. But the weight and size increase was obviously considerable and the technique a difficult one for the time, and the requirement was outdated before the device matured. We have our own record in Britain. One must admit the reduction of radiation drag by proper shaping of entry and exit ducting as prior art. More recognisable were attempts to give a temporary speed boost to wartime fighters by means of ram-jets. These schemes too were overtaken by events and, although ground development was physically successful, nothing directly useful emerged in time to meet a fleeting need.

There have been attempts to compound the ram-jet with the rocket in several ways, for example by regarding the ram-jet as a thrust augmentor for the rocket or the rocket as an air inducer for the ram-jet, and more subtly, by expanding the rocket gases (diluted by excess fuel or oxidant) in a turbine to provide power for compressing an air supply to the ram-jet at lower flight speeds. These schemes lack the simplicity of either rocket or ram-jet and still pay the price of oxidising with anything but free air. Offering neither the small bulk and high specific thrust of the rocket for short endurance, nor the good economy of purely air breathing systems for extended operation in climb and cruise, they should be regarded with suspicion as possible low speed auxiliaries but on no account as members of the ram-jet family.

Only the guided weapon has yet given the ram-jet a real job to do. The weapon, whatever its sustainer motor, is launched ballistically to supersonic speed under high acceleration by jettisonable rockets, partly to lighten, cheapen and simplify the weapon itself and partly to reduce time to interception. Here thrust deficiency at low speeds is immaterial and good economy, light weight and relative simplicity in the supersonic speed band make it an attractive motor for all but the shorter ranges in which the solid rocket will serve.

Missile engines tend to be specialised. Their first job is to provide some acceleration or, at least, hold speed in a steep climb. They work at high ram pressures near the ground and are able to put in kinetic energy low down to help ascent at high altitudes where ram presure, mass flow and thrust have all fallen in relation to weight. Thereafter they must maintain speed at lower thrust ratings against drag forces only. Their job and operating conditions therefore differ from those of prospective aircraft engines, where the ram pressures must be limited by aircraft stress factors and high longitudinal accelerations are unlikely, but steady acceleration will be needed from the main engines. Since the war there has been widespread use of flight test vehicles framed to provide a means of trying out ram-jet propulsion techniques under representative conditions, and latterly, of course, some actual weapon engines. Now, individual missile or aircraft engines must be closely matched in size and operation to their special role or may even be integrated structurally and aerodynamically into the systems they power. The ram-jet is therefore a subject where a wide variety of component techniques and operating phenomena deserve study because of the extreme range of possible requirements and methods of application.

Performance and Design Factors

The latent performance of a ram-jet at any speed is set partly by pressure recovery, or internal aerodynamic efficiency, and chiefly by combustion temperature.

Securing the performance depends upon proper choice of critical flow areas at inlet, inlet throat, and nozzle throat, and so on, to give proper matching of components.

Figure 2 shows the performance factors, thrust per unit area and pressure and specific fuel consumption for families of engines designed with optimum matching at $M=2{\cdot}0$ and $M=3{\cdot}5$ in terms of combustion temperature and the major geometrical factors or ratios of inlet capture and exhaust throat areas to combustion chamber area. The two speeds selected are far enough apart to illustrate important area variations and the general problem of design over a wide speed band. Thrust is expressed with respect to combustion chamber area, the only handy constant since at high speeds intake area can exceed combustion area. For illustration the exhaust expansion is taken to be loss free and quite low intake recoveries are used. These lower values are appropriate, partly because the argument to be developed does not turn upon precise values, partly because they are compatible with simple cowl shapes of low drag and partly because they are compatible with operation over a wide speed range, especially with variable geometry when optimum recovery cannot be expected everywhere. The sensitivity of results to design assumptions is considered later. In all cases the exhaust nozzle is expanded back to maximum area, and the thrust and specific fuel consumption (s.f.c) values allow for external friction and wave drag as appropriate.

At $M=2{\cdot}0$ maximum thrust lies in the region of intake area 0·4 at high flame temperature with exhaust nozzles of 0·8 to 1·0 and an s.f.c. of about 3·5 to 4·0. Optimum fuel consumption of about 3·0 occurs with lower temperatures, an intake area of 0·5 to 0·6 and an exhaust throat area about 0·8 at approximately 60 per cent of maximum thrust. In the $M=3{\cdot}5$ case, maximum thrust again lies at high temperature and large nozzle throats, but with intake areas of approximately 1·0, the s.f.c. remaining near 3·5 to 4. To maintain maximum

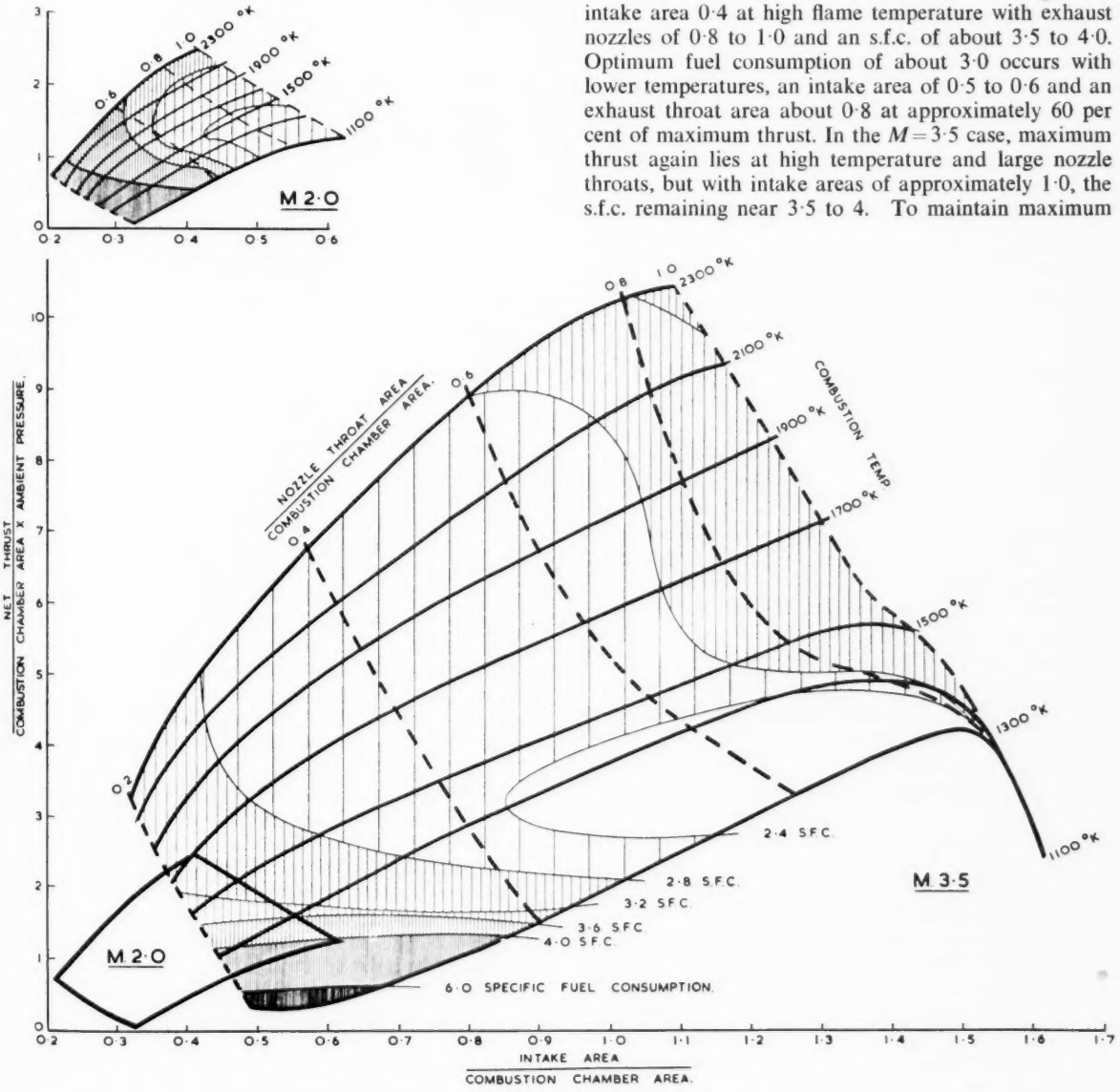


FIGURE 2. Ram-jet design characteristics at $M=2{\cdot}0$ and $M=3{\cdot}5$.

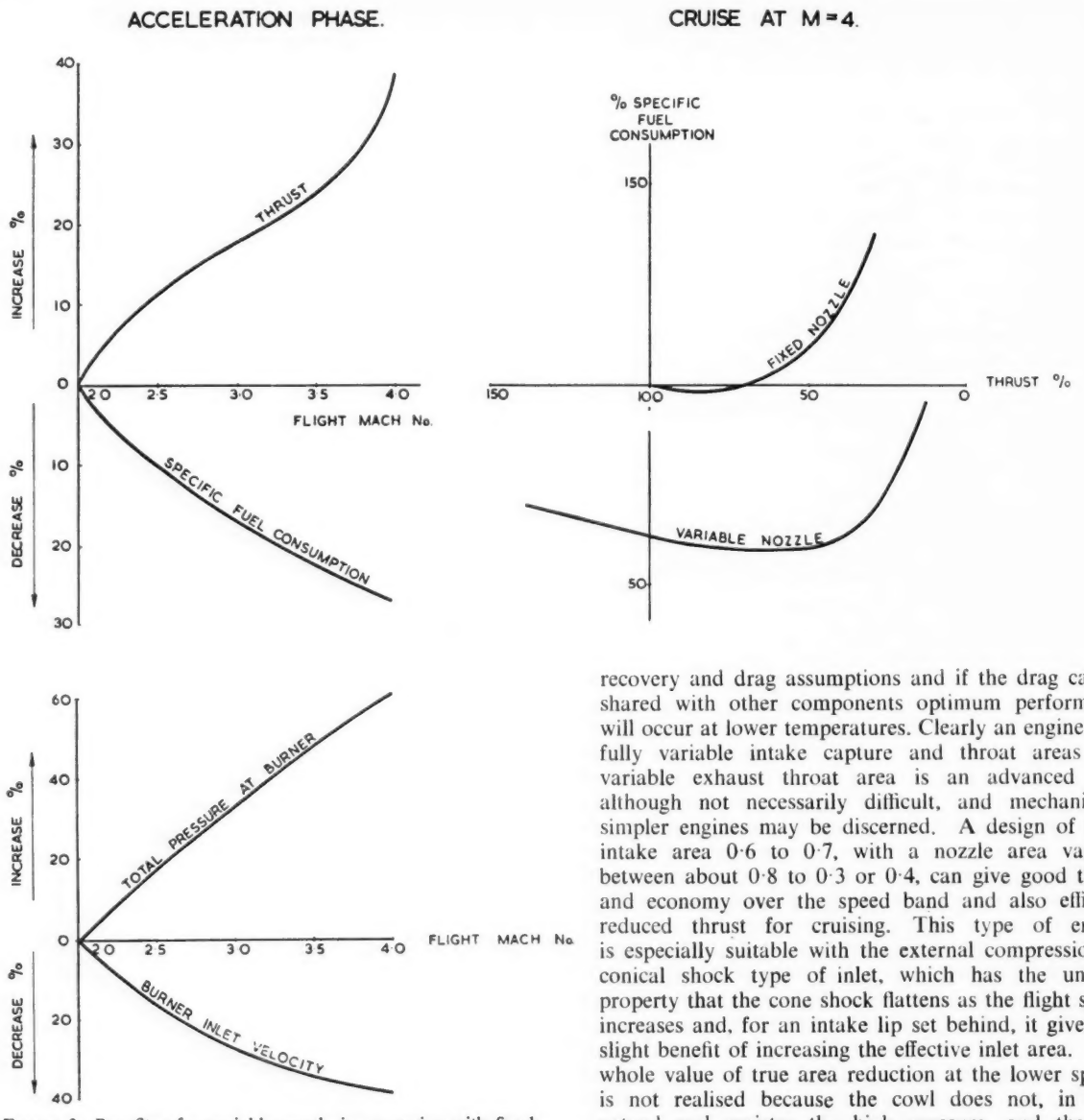


FIGURE 3. Benefits of a variable nozzle in an engine with fixed intake.

thrust we need an engine with fixed full exhaust throat, high exhaust temperatures and an inlet area varying from about 0·4 to 1·0. In the course of acceleration F/P will increase by a factor 4.

It is clearly possible then to provide an engine which, simultaneously climbing and accelerating, provides roughly constant thrust over a large change of height. This latent acceleration and climb capability is a very handsome start to supersonic flight. If, now, at high speed the nozzle is closed and the temperature reduced (accompanied by closure of the intake) one can drop down to a quarter of maximum thrust with a drop of some 40 per cent in specific fuel consumption. The precise values achieved depend, of course, upon recovery and drag assumptions and if the drag can be shared with other components optimum performance will occur at lower temperatures. Clearly an engine with fully variable intake capture and throat areas and variable exhaust throat area is an advanced one, although not necessarily difficult, and mechanically simpler engines may be discerned. A design of fixed intake area 0·6 to 0·7, with a nozzle area varying between about 0·8 to 0·3 or 0·4, can give good thrust and economy over the speed band and also efficient reduced thrust for cruising. This type of engine is especially suitable with the external compression or conical shock type of inlet, which has the unique property that the cone shock flattens as the flight speed increases and, for an intake lip set behind, it gives the slight benefit of increasing the effective inlet area. The whole value of true area reduction at the lower speeds is not realised because the cowl does not, in fact, extend and register the high pressure, and the full design thrust corresponding to Fig. 2 cannot be achieved until the speed is reached at which the shock is incident. Finally there is our present-day workhorse, the fixed geometry engine, which earns our bread and butter.

Without a variable nozzle we see that it is impossible to match a fixed intake with a constant reasonably high maximum temperature over a speed range. If the design is biased towards good thrust at high speed the intake area is large, and spill or blow-off drag must be incurred at low speed, with loss in thrust and economy. If the design is biased towards low speed, the high speed thrust and economy are cut off by limited air flow, and the internal pressure must fall below maximum values to maintain choking velocities at the nozzle throat. In effect, shock and mixing losses are allowed to develop

within the intake to reduce the pressure to the value matching the nozzle flow coefficient. If the temperature is reduced at high speeds this process can go a stage farther towards lower thrust.

The characteristics of such a fixed geometry engine are compared in Fig. 3 with those of an engine of variable exhaust geometry. Starting with equal performance at the design Mach number of 2, 20 per cent of thrust is lost by a Mach number of 3, specific fuel consumption is up to 20 per cent, combustion chamber pressure has fallen 20 per cent and combustion chamber velocity has increased by 50 per cent. This is not the whole tale of woe. Diffuser air flow is disturbed and irregular patterns develop which create operating difficulties of their own, aggravating combustion difficulties due to low pressure and high velocity. These effects are described in some detail later. Further increase in specific fuel consumption occurs with reduction of thrust below the maximum.

There are then, these three main categories of engine ranging from the evidently mechanically complicated to the apparently simple, with concurrent deterioration in thrust and performance. Short range weapon engines are typically in the "third class." In extenuation of the missile engine it must be pleaded that the fuel weight consumed is comparable to engine weight and weight due to mechanical complication rapidly eats up fuel saving, especially since the engine does most work at the lower speeds and altitudes where its design is relatively efficient. This type of engine is therefore entirely right for its purpose, but it is not necessarily the easiest to develop. The more complicated versatile engines may well turn out to be easier after all.

There is a warning to sound about too ready acceptance of the thrust picture painted here and this concerns thrust sensitivity to the design variables, including some not yet mentioned, and the whole subject deserves discussion. For example, if an engine of fixed exhaust geometry achieved only a lower intake recovery pressure than expected, then mass flow and thrust would fall in rather greater proportion. Thrust can only be restored if the nozzle throat can be increased with, or without, an increase of temperature. A low thrust, high efficiency cruising engine with variable geometry is, in fact, not sharply critical to pressure recovery. Lower pressure recovery requires less exhaust expansion area ratio and the nozzle can be opened to match approximately the revised pressure ratio and flow. As long as the design lies in the low s.f.c. region little harm will be done. The net effects are quite similar to the simplified account given in Fig. 1, where halving pressure recovery led to 20 to 25 per cent drop in overall efficiency. Internal drag or pressure loss is interchangeable directly with intake recovery, and one can therefore see immediately that a combustion chamber loss of 5 to 10 per cent of intake pressure is tolerable. Again, total pressure loss in the nozzle has almost the same effect. It introduces a slight change in net thrust per lb. flow which can be compensated by slight increase in mass flow or temperature, or both, provided that the design is in the right region for economy and therefore generally insensitive to these

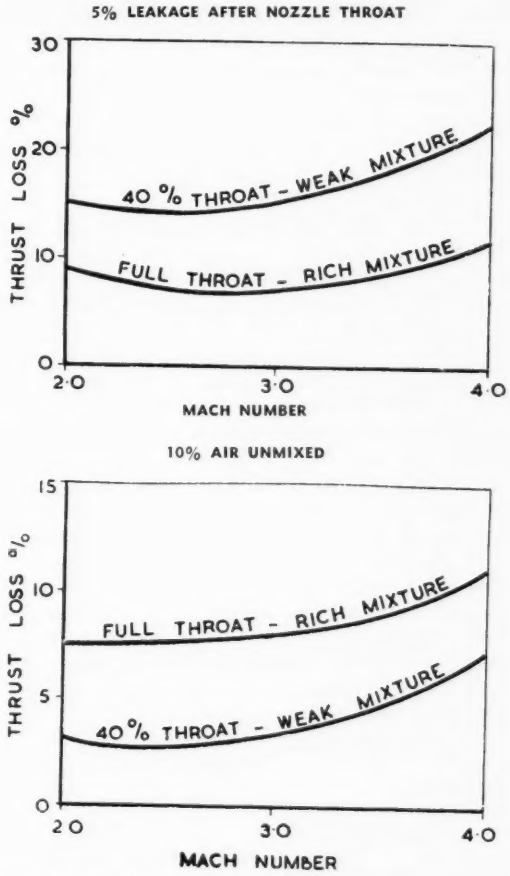


FIGURE 4. Sensitivity of thrust to leakage and incomplete mixing of exhaust gases.

variables. Naturally this loss becomes more significant as the degree of expansion increases, *i.e.* with flight Mach number and lower temperature of operation. At maximum thrusts with full throats and limiting temperatures, thrust loss due to total pressure loss cannot be compensated, but again s.f.c. will not suffer much.

However, at the higher Mach numbers and especially with low combustion temperatures, net thrust is progressively more dependent on the difference of two large quantities, inlet and outlet momentum, and one must guard against forms of loss of outlet momentum which are magnified into large losses of net thrust and necessarily accompanied by an increase in s.f.c., even when thrusts are restored by raising temperature or mass flow. Fig. 4 shows the effect on net thrust of gas leakage in a variable nozzle and of non-uniform outlet temperature distribution on high and low thrust engines over a range of speed. Leakage represents a direct loss of outlet momentum proportional to the flow loss. Thus if δ is the fractional flow loss, the net thrust loss fraction will be

$$1-\left(\frac{\text{inlet momentum}}{\text{outlet momentum}}\right)^{\delta}.$$

which can mean a large change both in thrust and fuel consumption. Moreover, if the outlet momentum is increased, say by increased temperature, to restore thrust a corresponding multiplying factor on s.f.c. must still apply. A high cost in s.f.c. cannot therefore be evaded and so, to approach the best efficiencies, any variable geometry must be fully sealed.

Thrust loss due to imperfect mixing is rather similar in its effects. The loss arises from the fact that a mass flow of gas under selected expansion conditions will develop an exhaust impulse effectively proportional to the square root of its total temperature. Unfortunately, two gas streams at dissimilar temperatures will yield a lower value of the mass mean of the square roots of the temperatures than the value of the square root of the mass mean temperature. This loss is proportionally greatest when the ratio of temperature of the mixed and unmixed fractions is greatest, *i.e.* at high temperature rises. The weak mixture engine tends to benefit from this, especially at high Mach numbers, but unfortunately the effect due to ratio of inlet to outlet momentum enters simultaneously and more than cancels the benefit. This effect leads to an inescapable increase in s.f.c. The whole story is that the really high speed efficient engines need high standards of mechanical and combustion design. Moreover, the requirement for absolutely flat temperature distribution will not be compatible with cooling requirements.

Intake Operating Problems

It is sometimes presumed that the serious problems of supersonic intakes are the creation of efficient shock compression patterns and subsonic diffuser shapes, and the estimation of the wave drag forces caused by compression on, or near, the intake cowl. Thereafter in design one simply chooses an intake and method of operation giving the best balance of recovery and drag for the flight plan in hand. For intakes with external compression by wedge or cone, often with a measure of internal contraction also, these performance factors have been fairly well known for some time, although refinement continues. But these intakes all deflect air ahead of the plane of inlet and then redirect air axially within the inlet, and this introduces many operating problems. Apart from drag associated with external deflection, the boundary layer built up on the deflector is acted upon by successive shocks varying both in position and strength with both flight speed and thrust in a fixed geometry engine. Above design speed the main deflecting shock system may also impinge upon the boundary layer formed along the inner surface of the outer wall of the intake and flight incidence effects also intrude. The consequence is that in a fixed geometry engine working over a range of speed and thrust, the space distribution of mass flow from the intake varies enormously and is, sadly, beyond our ability to account for analytically. The professional aerodynamicist restricts himself to the serious problems and cheerfully leaves the distribution to be swept up and incinerated within the combustion chamber. But this is not all; should the combustion system excel itself or, more likely, the control system lapse, thereby overdoing the temperature with reduction in mass flow, the intake reserves the right sometimes to go unstable. Providence surely intended better things and one longs for the day when mechanical ingenuity is allowed to provide adjustable throats and diffuser angles with improvement to flow distribution and matching.

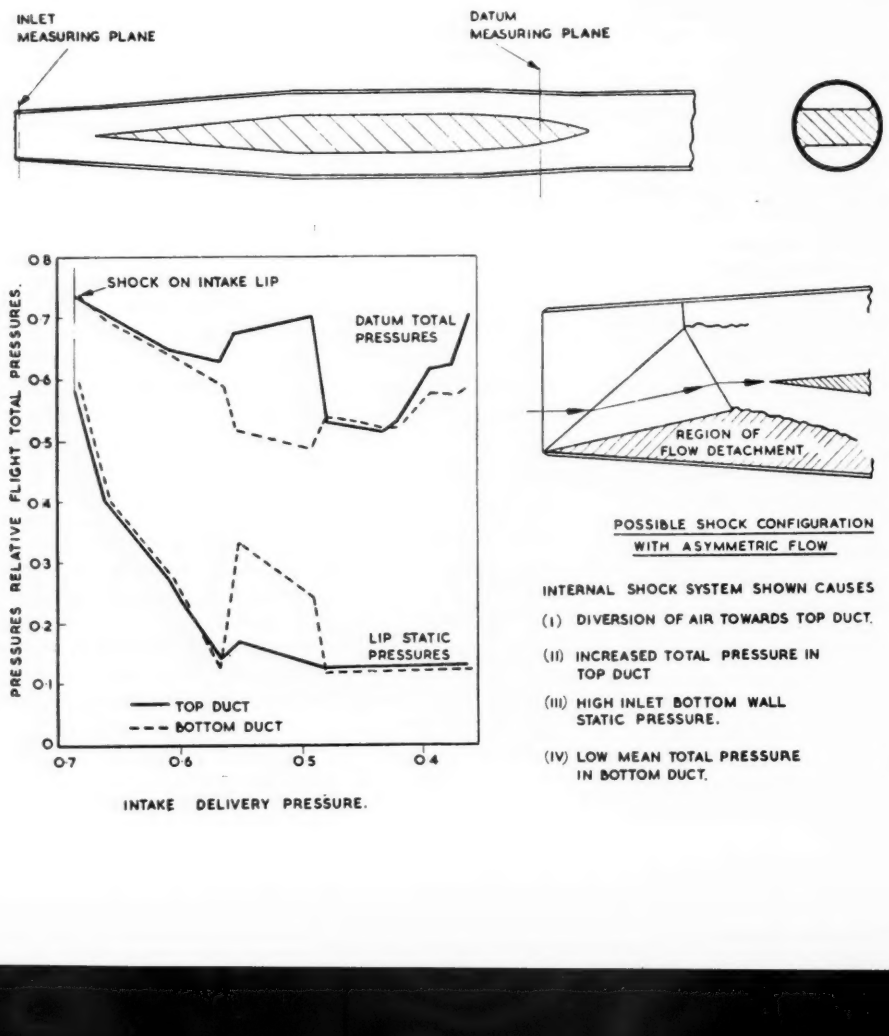


FIGURE 5. Asymmetric flow in a Pitot intake at a flight Mach number of 2·0.

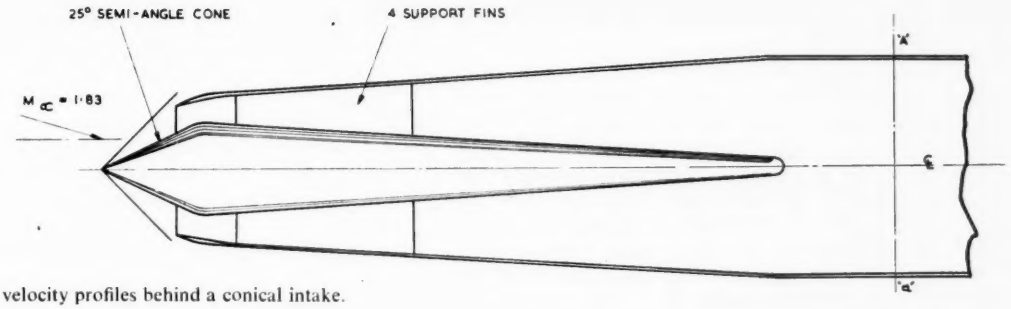
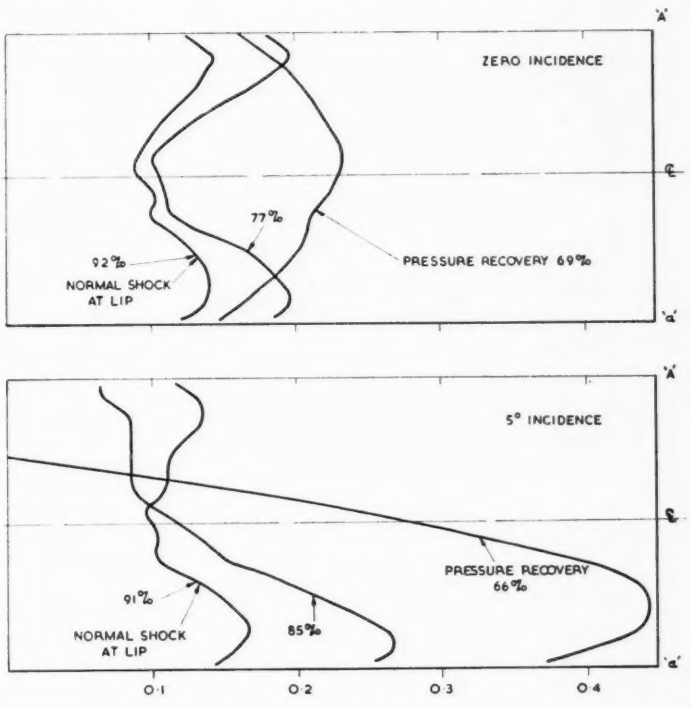


FIGURE 6. Typical velocity profiles behind a conical intake.



Even a Pitot intake, stable though it is on flow reduction and relatively insensitive to incidence, is not necessarily immune from supercritical operating troubles. We met one such difficulty while flying a test vehicle (described later) at Mach numbers above those we had at first been able to test on the ground. The intake configuration concerned is shown in Fig. 5 and consisted of a flat storage body within the intake diffuser splitting the duct into two passages. The pressure plots record measurements taken on a model at $M=2{\cdot}0$ as the degree of supercritical operation increased or, if you like, as pressure recovery was allowed to fall off. Over part of the range of recovery values the flow split unequally between the two ducts; the duct with the lesser flow also gave the lower total pressure but higher static pressure, and this higher pressure seemed to extend forward to the plane of intake on that side. This suggested the shock pattern shown inset, and simple two-dimensional calculations assuming this pattern gave about 10 per cent agreement with the observed distribution of flow and pressure. Oddly, on winding up the pressure recovery again, the flow consistently split in the same manner but with bias to the duct opposite to the case of decreasing recovery. No combustion chamber likes these flow variations, and a simple remedy was to extend a splitter plate forward from the storage body to the plane of inlet.

Figure 6 illustrates the tougher problems of this sort arising with external compression intakes. The model shown has its design point (cone shock incident on cowl lip) at $M=2{\cdot}1$ and the tests were done at $M=1{\cdot}83$. At zero incidence and maximum recovery outlet distribution is symmetrical and reasonably uniform, although a trough exists in the centre body wake due mainly to the action of the throat shock on the cone boundary layer. As the degree of supercritical operation increases, stronger shocks develop progressively farther within the diffuser. First the centre body wake becomes more pronounced, but at last interference on the outer wall predominates and the mass flow trough in the centre of the duct is replaced by a peak, while minimum velocities occur in the outer part of the duct. Incidence can create still more powerful effects; at full recovery flow follows the direction of incident air and supercritical operation can magnify the bias and even lead to recirculation of air. At speeds above $M=2{\cdot}1$ the cone shock enters the intake to produce further distortions.

In a long engine with ducting between the intake and combustion chamber, the extremities of these distributions have time to mix out, but in short engines combustion chamber design must somehow allow for them. The use of a variable nozzle would maintain the position of the throat shock so that only relatively small change of air distribution would occur over a range of speed and thrust. Meanwhile for the "simple" engine it is worth seeing what can be done to control

distribution. An obvious method is to redistribute air physically within the intake.

A useful device is illustrated in Fig. 7. It is a sandwich sampling scoop taking radial slices of air and delivering alternate slices to the top and bottom of the passage. For low loss the angle of the scoops must not be too steep, and they are preferably cut-off at the downstream end to give, in effect, a short circuit for air in the mid-regions of the passage. Two-dimensional duct traverses just after the scoops show that the effect is primarily to yield three velocity peaks spaced across the duct for a single displaced peak approaching, but little reduction in the velocity amplitude. The benefits are that when the position of peak approach velocity alters, the discharge velocity peaks remain in the same position, while the multiple peaks mix out the velocity amplitude faster in a given subsequent length of passage. In this process the wakes of the scoops assist. Pressure loss at supercritical conditions is not relevant,

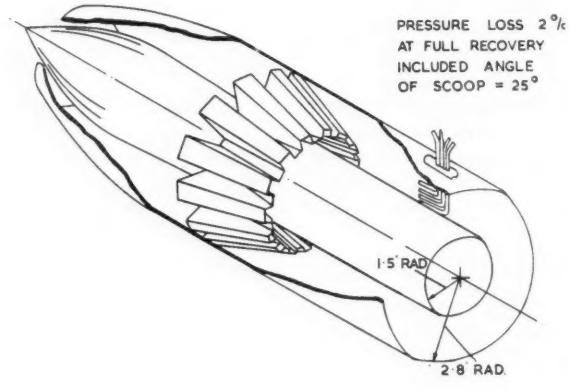


FIGURE 7. Flow rectifier in a conical intake diffuser.

but the loss at critical conditions is a direct loss of maximum recovery. The pressure loss of this device is about 0·2 approach velocity heads, and it can be installed as shown in a diffuser at a plane where the mean Mach number at full recovery is about 0·35 for a loss in maximum recovery of 2 per cent. The improvement it secures when installed in this way is also shown for the case of zero incidence.

In many combustion chambers fuel is injected within the intake upstream of the combustion chamber and the intervening diffuser space constitutes a fuel mixing and carburation zone. Changes in mass flow distribution then lead to changes in mixture strength distribution in the combustion chamber, and of the two the latter is probably the more important direct effect. It is true however that the percentage variation in mixture strength is typically only one half that of mass flow; combustion equipment will usually, but not necessarily, continue to burn in such circumstances. Indeed, engine stability range may in some cases increase, but specific fuel consumption will increase. But primarily it is changing distribution, rather than bad distribution, which leads to operational difficulty.

Intake instability is a rather different issue. Should an engine inadvertently enter this region of intake operation the flame may go out, or the engine may continue to oscillate indefinitely or, it may recover with change of operating conditions. There is no universal rule. But most intakes have some range of stable flow reduction at lower speeds and, accepting a loss of latent thrust somewhere over the flight speed band, operations can be planned to avoid the unstable region. However, a little interesting work has been done on an automatic stabiliser or "shock catcher" which can prevent the worst effects of intake instability. It is shown in Fig. 8. A plain cylindrical shroud of diameter greater than the inlet is mounted ahead of the inlet and an axial gap left between the two. This shroud adds only slight drag due to friction, and during normal operation of the intake it has no effect on its behaviour. Should the design shock system become unstable then, during oscillation, it enters the shroud and immediately "pops" forward to emerge as a normal shock ahead of the shroud. The system now acts stably as a Pitot intake at lower recovery, and excess air the engine cannot swallow at this lower recovery is leaked through the axial gap. Owing to the mass flow change the device can only be used over a range of Mach numbers where the associated change of mixture strength does not exceed the combustion chamber mixture limits. To return the system to normal duty fuel flow must next be reduced, while the total out-flow area (bleed area plus intake throat) is closely explained by the minimum contraction rules for internal compression intakes. After restarting, the mixture strength will be weaker than normal and the intake running supercritically, so the last action is to increase the fuel flow again towards the limit defined by intake stability.

All supersonic flow systems require variable geometry for the best results over a range of Mach numbers, and here one would like to push the shroud

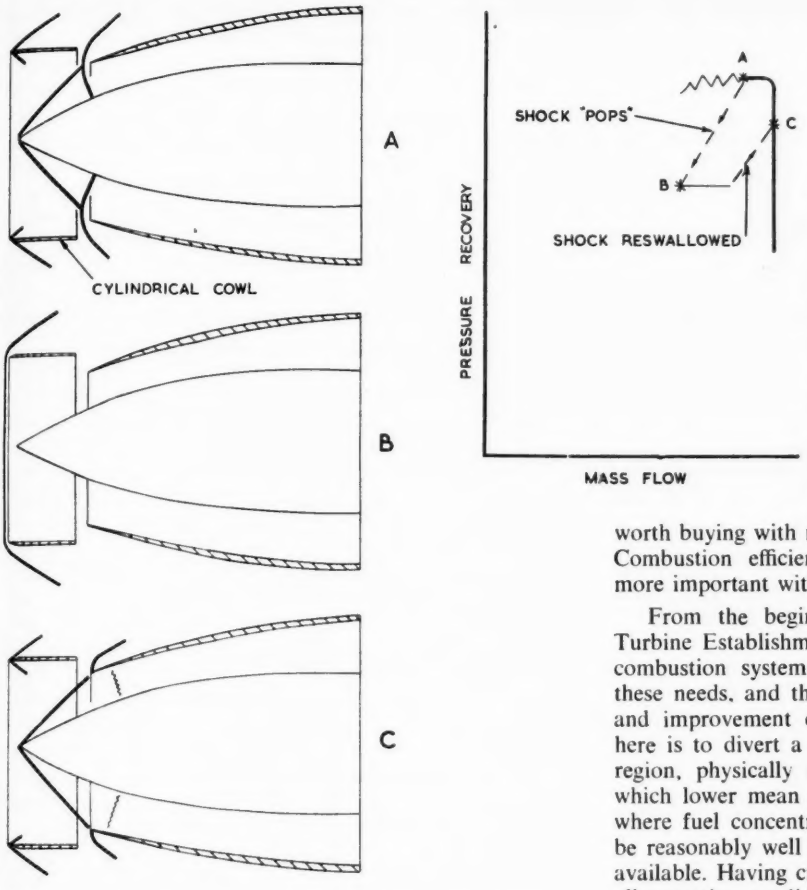


FIGURE 8. Prevention of flame out due to "buzz" by intake cowl.

forward and increase the spill flow area with Mach number. Obviously this device and its associated fuel control technique do not mate with the requirement for simplicity in a missile engine. Ideas that really work are rare and other circumstances may find employment for this one.

Combustion

In the early days of ram-jet endeavour the combustion problem was second only to the greater difficulty of getting equipment with which to solve it. A top limit on internal drag losses of 10 per cent of diffuser pressure means that in a high thrust system (diffuser discharge Mach number of 0·15 to 0·20) the internal loss coefficient certainly should not exceed 5. Physically this means that port or injection velocities cannot be large in relation to the mean axial velocity through the combustion chamber, as they are in a gas turbine. Put more simply still, there are tight limits on one's ability to blow fuel and air mixture about within the combustion chamber and make it go to all the places it should and then mix with igniting material already there. In terms of heat release per unit volume the high flow velocities can, or rather must, be compensated by extra burning length. Ram-jet combustion chambers are usually 3 to 6 ft. long and this, combined with high scrubbing velocities, obviously introduces a cooling problem. The requirement for reduced mixture strength at cruise after climb has already been explained. On short range engines, *e.g.* for interceptor missiles, most fuel is used in acceleration and climb at low level. In this case combustion efficiency at full thrust takes precedence over efficiency at weaker cruise mixtures. But a few per cent of efficiency in either régime is not worth buying with noticeable increase in engine weight. Combustion efficiency, especially at cruise, becomes more important with increase of range.

From the beginning, work at the National Gas Turbine Establishment has tried to establish a type of combustion system adaptable, with variations, to all these needs, and the constant theme has been the use and improvement of pilot systems. The simple idea here is to divert a fraction of the air into a sheltered region, physically separated from the main flow, in which lower mean axial velocities are maintained and where fuel concentration and gas mixing patterns can be reasonably well controlled within the pressure drop available. Having created a stable flame, efficient under all operating conditions, it is used to ignite the remaining fuel and air by-passing the pilot. This constitutes a two-stage system where thrust is altered by cutting off fuel supply to part of the by-pass air only, still leaving the cruise fuel to burn at optimum conditions throughout the thrust range. This technique is now very widely used and seems obvious, but its virtues were not always universally seen or admitted.

The pilot has taken different forms with growth of understanding and experience over an ever widening range of operating conditions. The first scheme, successful for its day, is illustrated in Fig. 9. The limit to baffle diameter was set by expansion loss in the flow around it, and this pressure drop was used to force air through the baffle at several places in such a way as to maintain continuous ignition by recirculation of burning gases. A pressure jet sprayed fuel symmetrically into the recirculation zone while secondary and tertiary fuel was sprayed at stages downstream. This system burned successfully at low altitudes but with marginal stability at maximum flow velocities. It was difficult to light at supersonic speeds and rather sensitive to assembly. But it powered the first supersonic ram-jet, a sufficient title to fame, and was a real invention at the time. Its basic limitations, apart from the need for high fuel pressure, were due to the small stabilising zone leading to a relatively small local heat output, so

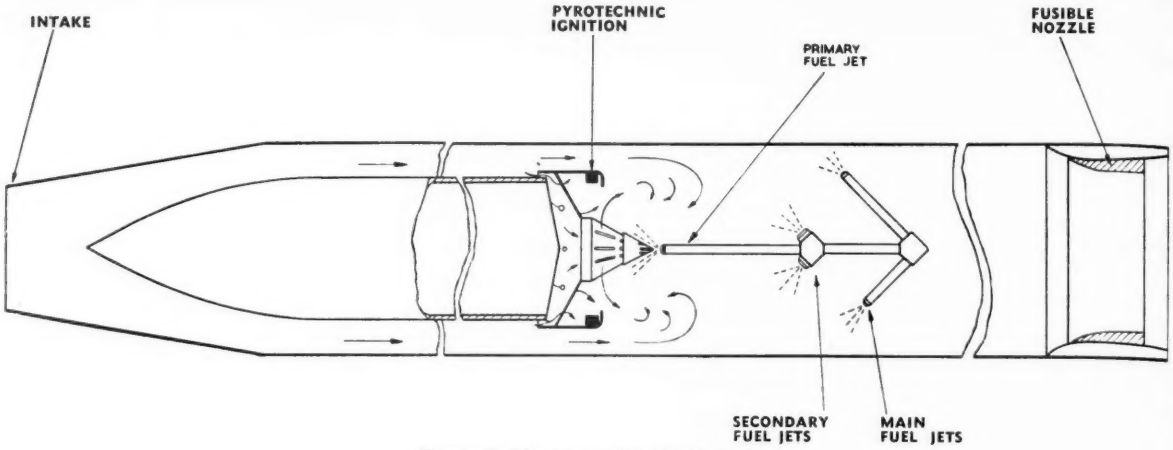


FIGURE 9. Pioneer combustion chamber.

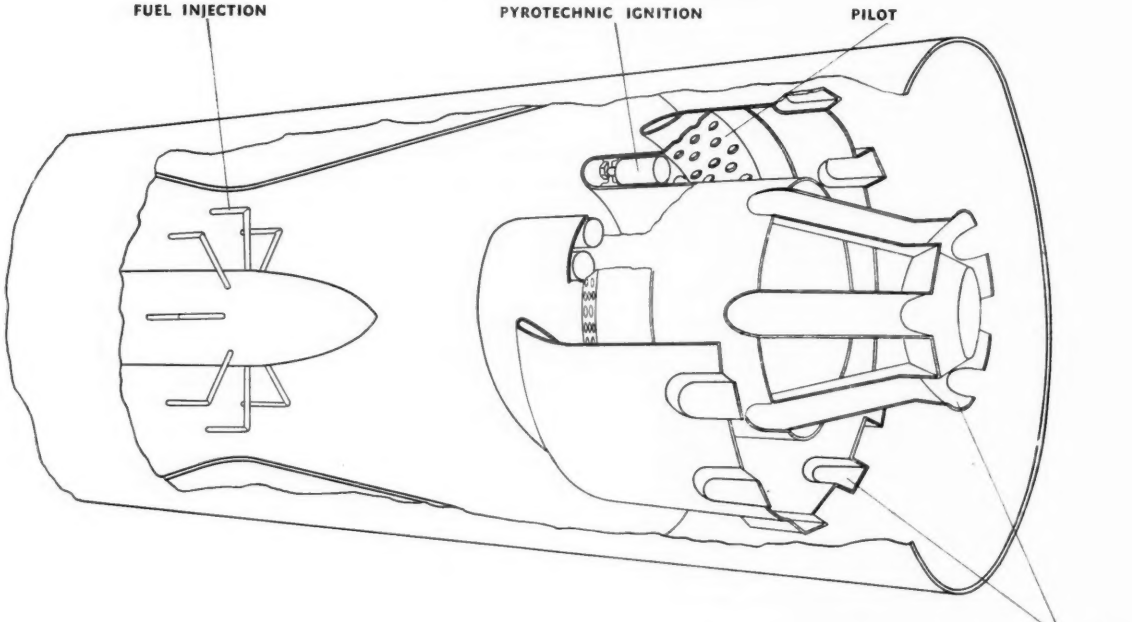


FIGURE 10. A stage in ram-jet combustion chamber development.

that at high loading the secondary mixture tended to extinguish the primary mixture. This is the fate of all simple systems of low pilot heat release and inadequate control of mixing-in of fresh reactants. Successive efforts have aimed at more vigorous pilots and adjustment to mixing-in of secondary flow.

It was soon realised that the high diffuser approach velocities were enough for good air blast atomisation, and that diffuser length could be used for the dispersion of fuel injected upstream and also, for evaporation at the ram temperatures met in supersonic flight. With the fuel already distributed and treated it was possible to put greater flows through the pilot. Fig. 10 is one example of this type on which a lot of experience has been accumulated. The pilot is of an annular form to split the by-pass air flow and reduce the lateral mixing distance from the pilot across the secondary mixture. Pilot mixture is collected by a ram intake and squirted through annular rows of small holes into the combustion zone. Here is a region of strong local recirculations and powerful mixing in which a stable flame is maintained at all conditions. Ignition is by short duration pyrotechnic flares tucked upstream and discharging hot products into the piloting zone. The flange obstacles mounted at the pilot delivery create wakes assisting the spread of flame through the secondary mixture, but these must not be overdone or uneven wall heating will result.

Systems of this general pattern have been studied in detail over a wide range of mixture, operating pressure and temperature, and variation of design. For example, fuel injection effects have been observed from points

near and far upstream, with early and late segregation of pilot air over a range of pilot zone volumes and air injection patterns and with many secondary mixing arrangements. Different linear scales of operation have been studied and also, such complete changes of layout as the use of circular instead of annular versions of the pilot.

As a whole results are consistent. For example, the farther upstream the injection station, the fewer jets are required, the more ignitable is the mixture and the more difficult it is to protect the pilot from mixture changes due to turn down of selected fuel jets for cruise. Low fuel pressures only are required, provided a clean air blast effect is secured by making sure that the fuel is thrown clear and does not dribble. Thereafter the lower the pressure the less variation there is in distribution with change in speed and altitude. These systems can all be made to work quite well, although increased care and refinement are needed for operation at low pressure and temperature. A thrust and efficiency characteristic typical of these systems is given in Fig. 11, which shows the two-stage process clearly. Little change would appear in this characteristic in a properly tuned system as the operating pressure is reduced to about 6 or 7 lb./in.^{2}, but thereafter deterioration is fairly rapid. The qualification "properly tuned" is a very real one. Odd things can happen in development, due perhaps to variation in diffuser profile with operating conditions, or the incidence of vibration in part of the range. Sensitivity of this kind is discussed later. For the moment it must be said that development should be tackled in a spirit of informed empiricism, with equipment for full-scale testing.

However, continual enquiry goes on into the crucial phenomena of combustion processes and rational ideas most certainly guide, even if they cannot wholly instruct, the development process. These investigations, although specialised, are so useful in defining design possibilities and explaining operating limits to the flight envelope that they deserve a brief summary.

The two factors setting ultimate combustion performance limits are the chemical reaction rates of burning gas of given composition and temperature, and the mixing rates and patterns achieved when fresh mixture is added continuously in a steady burning and flow process. Together these determine the local conditions and burning rates at which combustion will occur in practical systems. In a notable and simple experiment using a spherical reaction vessel fed uniformly with high pressure ratio jets, and exhausted uniformly through multiple holes, Dr. J. P. Longwell[1] was able to measure heat release rates over a wide range of physical and chemical conditions in the absence of any apparent mixing rate restrictions. At the National Gas Turbine Establishment we use an indigenous correlation of these results in which the mixture limits for stable heat release and the combustion efficiency at stable operating conditions are convincingly shown to be unique functions of a loading parameter

$$\frac{Q}{VP^2e^{T/n}}$$

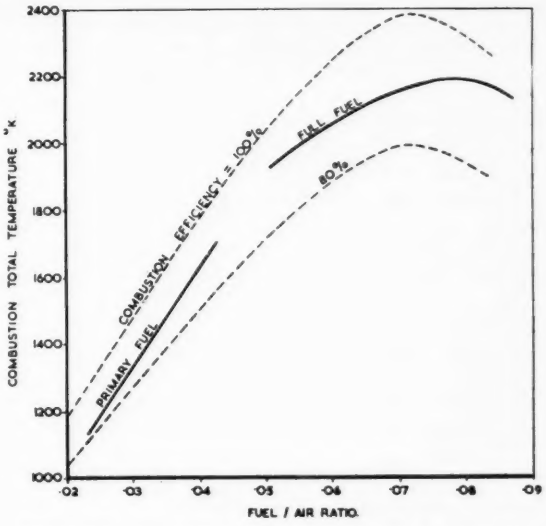


FIGURE 11. Two-stage combustion chamber characteristics.

where Q mass flow rate of air
V combustion volume
P pressure
T mixture supply temperature
n function of fuel/air ratio.

These relations are shown as the reference curves in Fig. 12 for the special case of mixture supply at 200°C. The ideal chemical performance is therefore known for normal fuels and effectively explained by theory useful from the engineer's point of view. The question of direct practical interest remains—what sort of loading and efficiency can, or should, be expected in normal flow systems using acceptable pressure drop in mixing? This issue has been studied at the National Gas Turbine Establishment using uniform fuel air mixture fed through perforations in flow models over a range of flow rate, pressure, mixing strength and linear scale. The last variable permits some distinction to be drawn between the separate chemical and aerodynamic effects of air pressure. Some experiments, illustrated in Fig. 12, in which stability, and efficiency and its distribution at outlet were measured, tentatively answer the practical question and also advance the understanding. The highest heat output and efficiency came from the use of a multiple hole arrangement in which jet distribution, penetration patterns and break up length are carefully arranged to give the most uniform outlet conditions. This may not sound surprising but it is more difficult to achieve and to prove than to say. The surprising thing is that with all arrangements performance is relatively insensitive to pressure drop as such. For example, uniform scaling down of hole sizes at constant flow has little effect. The critical point is that a sufficient number and distribution of holes must be used with sufficient pressure drop to give the penetration patterns leading to uniformity. Ten per cent pressure drop was certainly enough to secure the maximum loadings obtained. The best loading and a related efficiency are compared in Fig. 12 with the

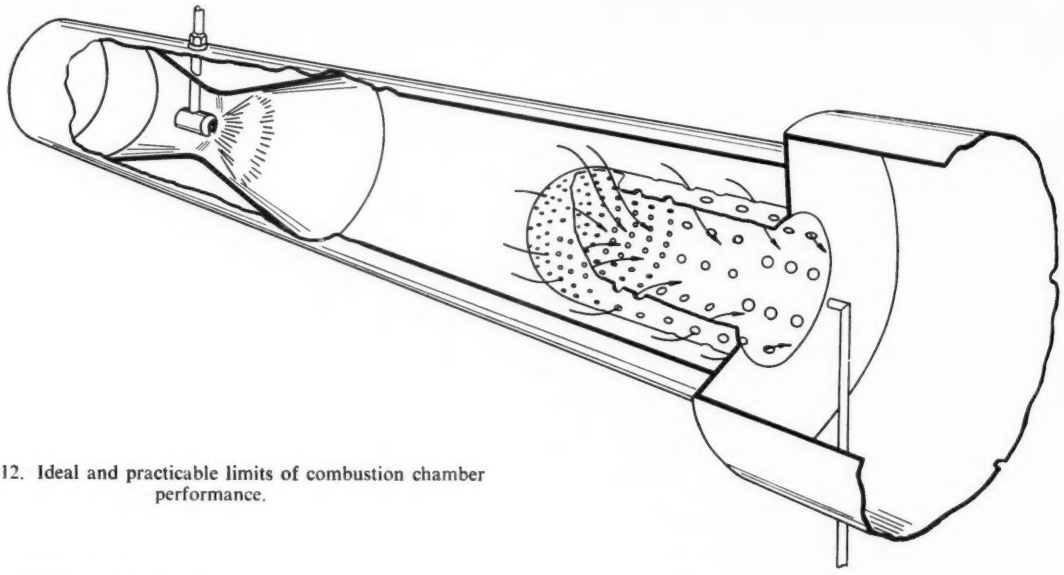
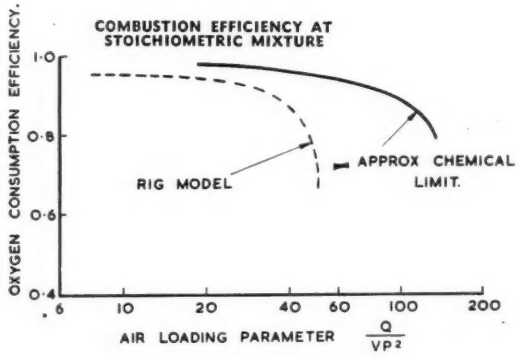
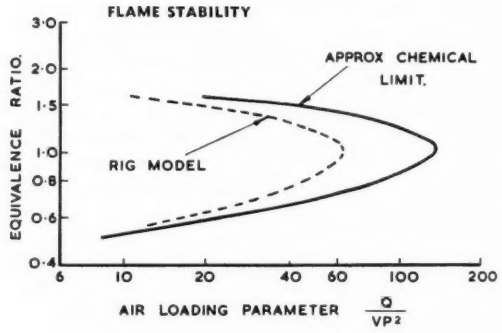


FIGURE 12. Ideal and practicable limits of combustion chamber performance.





reference chemical limits. The loading fraction achieved increases from 30 per cent at stoichiometric to 70 per cent at an air/fuel ratio of 25, reflecting the changing balance between mixing and reaction rates. The performance of these "practical" idealised systems does not, of course, correlate with a parameter derived from chemical considerations alone, as is implied by the rough comparison of Fig. 12. The performance also depends upon a Reynolds number characteristic of the system and the true correlating parameter takes the form

$$\frac{Q}{VP^2}(Re)^a.$$

As one might expect "a" is quite small, 0·08, for well mixed systems but may increase to 0·3 in less efficient, poorly mixed systems. Curiously, it appears to be a constant for any one system and does not change with mixture strength.

Although the preceding ideas and results may be used to define the size and operating conditions within which development for a given purpose is likely to be successful, they do not constitute a system of detailed practical design.

In practice fuel distribution is not uniform and varies with flight conditions, as does fuel state also. Again, air vibrations introduce changes in mixture patterns and mixing rates, while a local deterioration in combustion due to locally inferior mixture conditions may upset later stages where conditions would otherwise be good. There are also the conflicting needs of uniform outlet distribution for good performance in the second stage, when working either as a dilution zone or as combustion zone, and for lower temperatures near the walls to assist cooling. For the best practical results an unprejudiced approach is still the best. One example of the puckishness of combustion system design was this. Excited at the prospects illuminated by recent researches, we modified a working combustion chamber to incorporate the best pilot that empirical theory could propose. Surprisingly no change in overall performance could be detected, but the fatigue life of the pilot was usefully extended due to the more regular metal temperature patterns set up; an unexpected bonus but very gratefully received.

Some Cooling and Mechanical Considerations

In a pod-mounted engine external air flow may be used for direct convection cooling of the combustion

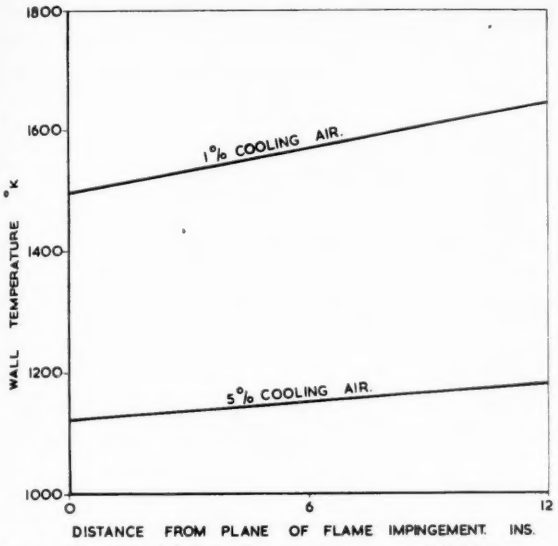


FIGURE 13. Calculated wall temperatures at 2,300°K gas temperature.

chamber wall. Useful heat is lost overboard and the tailpipe is exposed to aerodynamic and inertia loads, but the practice is justifiable where weight is more critical than economy. N.G.T.E. has experimented with internal cooling of submerged tailplanes. Calculations on cooling are always depressing. Fig. 13 gives some computed wall temperatures for a pipe passing less than maximum flow at 2,300°K and cooled by air passing at 150°C through a surrounding annular passage. Even with 5 per cent of cooling air, high temperatures of 1,000°C result. One must, therefore, cheat.

There is now considerable experience of the arrangement shown in Fig. 14. About 3 per cent of ram air is fed through the liner into the cooling annulus well ahead of the pilot and definitely before any fuel can mix with it. The liner is anchored upstream, it is free to expand

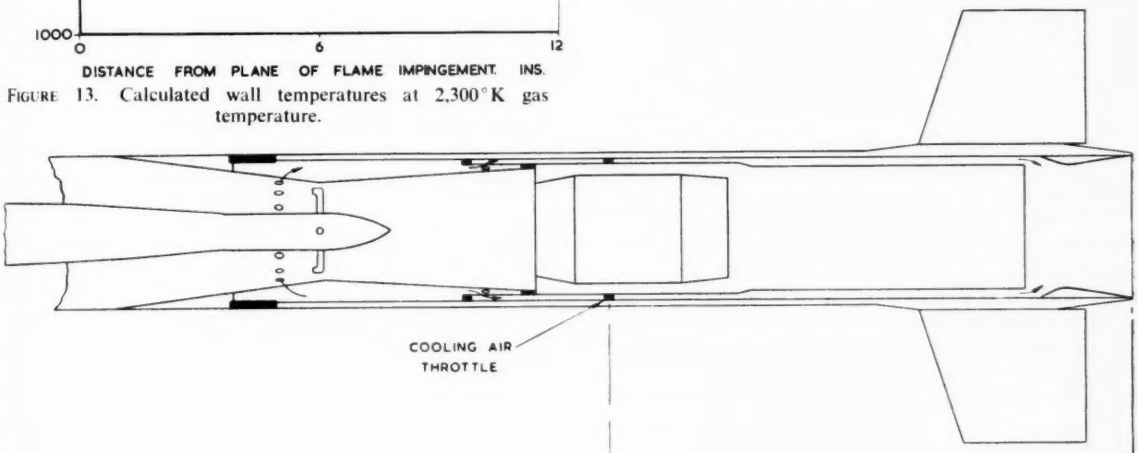
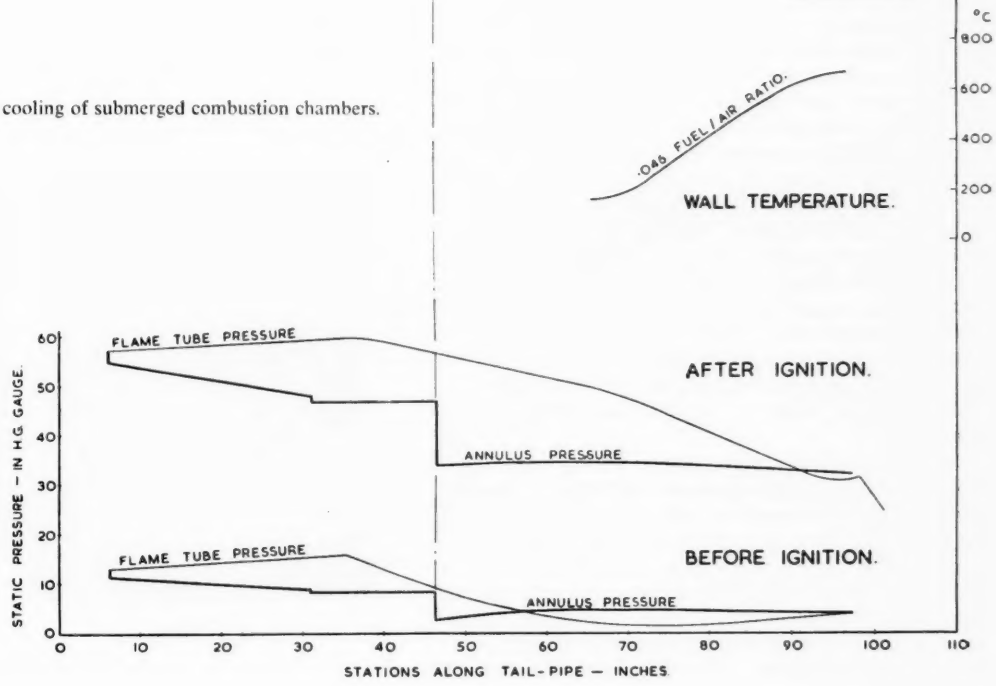


FIGURE 14. Air cooling of submerged combustion chambers.



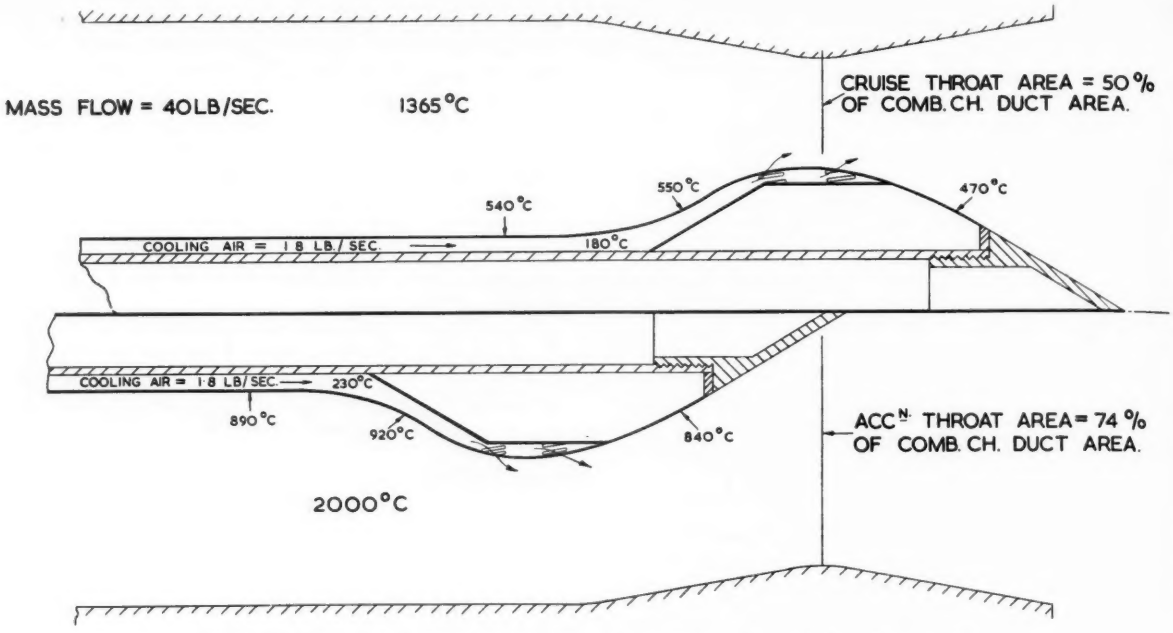
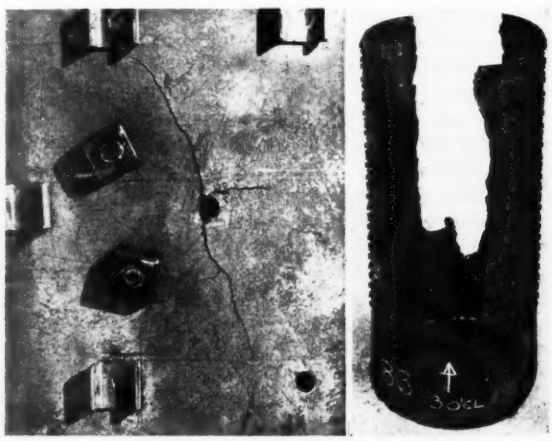


FIGURE 15. Typical wall temperatures observed in operation of a variable exhaust nozzle.

downstream, and is tapered in the cold state to permit radial expansion at the hot end. The cooling air is heavily throttled at the plane of the pilot to ensure that only compressive loads of small value and extent are developed by the pressure fields arising in supersonic flight, both before and after ignition. The liner should therefore be light and run at high temperatures. Here again theory is only a rough guide. Expansion allowances and wall temperatures are established by trial, while the heat load is adjusted by tuning the fuel, air and gas temperature distributions. With these aids one can run regularly at overall mean temperatures of 2,100°K and ram temperatures of 200°C, and the system has successfully flown many times. Rather similar ground experiments have also been successful in cooling and operating a plug type variable nozzle. Fig. 15 shows some of the temperatures measured in such a nozzle under both high and low thrust conditions. With 4 per cent cooling air a movable plug has been run up to mean gas temperatures of 2,300°K. But these cooling examples must really be taken with the tailored characteristics of their associated combustion systems. Indeed, the mechanical design and performance of the combustion chamber, the nozzle and the cooling system must be worked out as one joint exercise.

This is especially true in view of the big part played by metal fatigue. Air vibrations of several types and frequencies are observed in all high velocity systems, but there is no exact numerical control or understanding of the amplitude developed in any of them, and a variety of fatigue failures can occur as a result. Should they occur the results are often immediately catastrophic. Fig. 16 shows a liner failure met in the course of development. Only a few seconds separate initial from total failure. One difficulty is that the more efficient flow patterns, which also provide most damping or scrambling of air vibrations, introduce more construction and material or opportunity for fatigue failure. Variations in metal temperature, even when regular, will be large and frequent, expansion allowances necessarily introduce freedom of movement, and stiffening devices introduce thermal stress and distortion and sometimes drag losses, whose secondary effects further complicate the problem. Acceptable metal temperatures, thickness, and weight, and required cooling flows, are therefore really determined in the limit by observed fatigue behaviour in very complex circumstances, and it is this fact above all others which dictates



(*a*) Initial failure (*b*) Total failure

FIGURE 16. Combustion chamber liner.

the need for ground test equipment simulating at full-scale the working densities and temperatures of flight. Fortunately the problem, although critical and only qualitatively understood, is not insoluble in practice. Experience is that it is only at ram pressures above three atmospheres that the difficulty becomes acute and then for the durations desired in ground development, rather than for missile flight times. At altitude conditions, unrefined designs of combustion and exhaust system will operate for many hours without difficulty. The rough picture is that for the durations and flight conditions where missiles or aircraft might operate, the ram-jet just gets away with it without obvious drastic weight penalties. One suspects that a reheated turbo-jet substituted in the same ram conditions would not escape so lightly.

Ground and Flight Development Problems

For ground development a ram-jet must have independent air supply and exhaust services. This bitter necessity was always an argument against the ram-jet, but ironically the bulk services it really required awaited the day when the turbo-jet, finding its own progress hindered by the same restrictions, commanded and shared even larger resources. Indeed, to retain his title the early ram-jet exponent had to be a real improviser. At N.G.T.E. we developed specialised designs of air ejector for altitude testing, we boosted them by heating the driving air to 2,000°K and flashing off steam to increase the driving mass and power, and temporarily, we had to modify Nene engines to supply air by bleeding. Even so, with one thing and another, our first 16 in. engine was actually flown when only one half section of it had been ground tested. But pre-occupation kept us from morbid envy of shining equipment in the U.S.A.

Those hands not scooping air from all Hampshire and puffing it through engines on ground test, took an occasional sacrificial engine to the coast. Hurled violently from a cliff, it clutched at brief distinction before plunging into an inscrutable sea, while wisps of telemetry bore back the riddle of its progress. No cosseting in cosy flying test beds for the ram-jet.

However, times have changed and we now possess in Britain elaborate and versatile ground test equipment designed for the job. One example will serve. Fig. 17 shows the new free-jet altitude cell at Pyestock. A free-jet nozzle is mounted on an articulated pipe system and directs a supersonic air stream towards the engine intake at varying incidence. The air jet can be supplied at any total pressure up to six atmospheres and at temperatures up to 300°C. Equivalent speeds and heights up to $M=3{\cdot}0$ and 70,000 ft. can be fully simulated. A bigger jet is blown at the engine than it consumes, so that intake shock reflections do not disturb the intake flow and the excess or "spill" air is efficiently diffused to mix later with the engine air discharged at the exhaust throat, and so reduce plant capacity demands. Techniques of "spill" diffusion have been intensively studied and those in use now are thought to be as efficient as possible. The process is a complicated one since the spill flow characteristics depend upon shape, Mach number, spill quantity, incidence, and engine intake design and operation. Fig. 18 illustrates the simple systems in use for testing at successive fixed Mach numbers of operation. The practice is to move the diffuser lip section forward to open up throat area for starting. It is advantageous in reducing pressure ratio demand for starting and for operation at incidence, to bleed some flow at true altitude pressure from the space around the jet and pump this separately back to the diffuser exhaust. Using all these aids it will be seen from the figure that the pressure ratios required for testing approach those of wind tunnels, where only small disturbance is caused by the test model to the diffuser flow. More versatile systems using rectangular geometry providing continuous and rapid change of test speed, height and incidence, have been studied in detail and are now designed but not yet built.

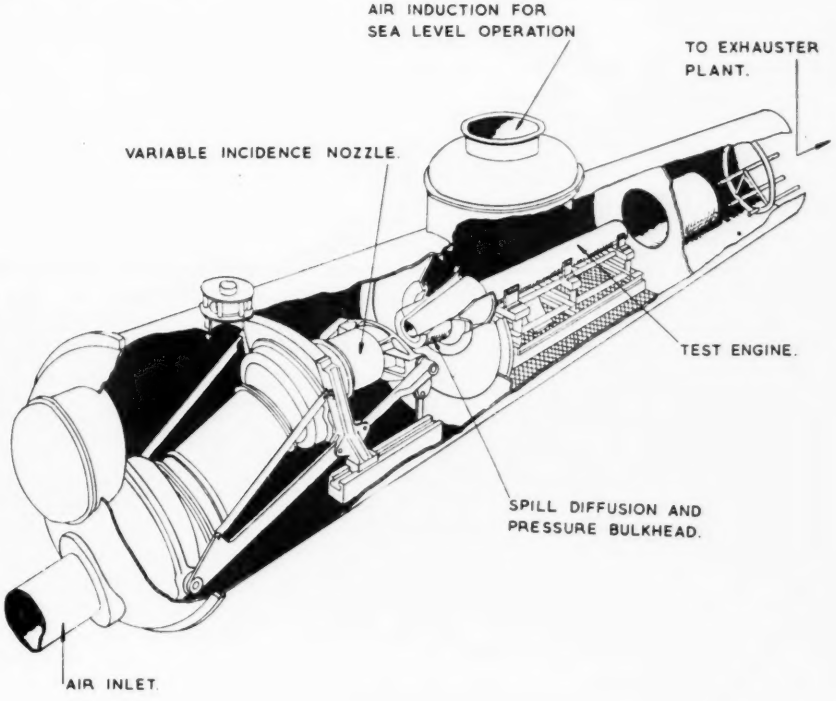


FIGURE 17. "Free jet" test cell.

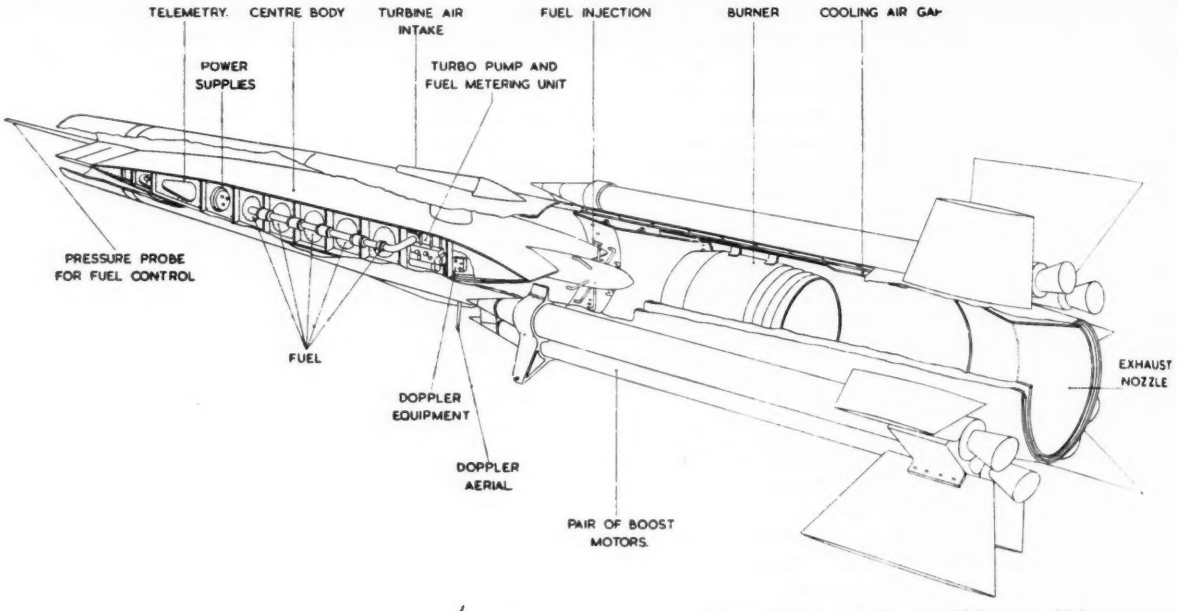


FIGURE 19 (*above*). Ram-jet flight test vehicle.

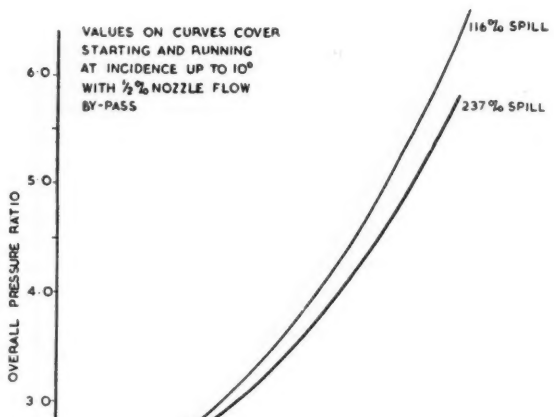
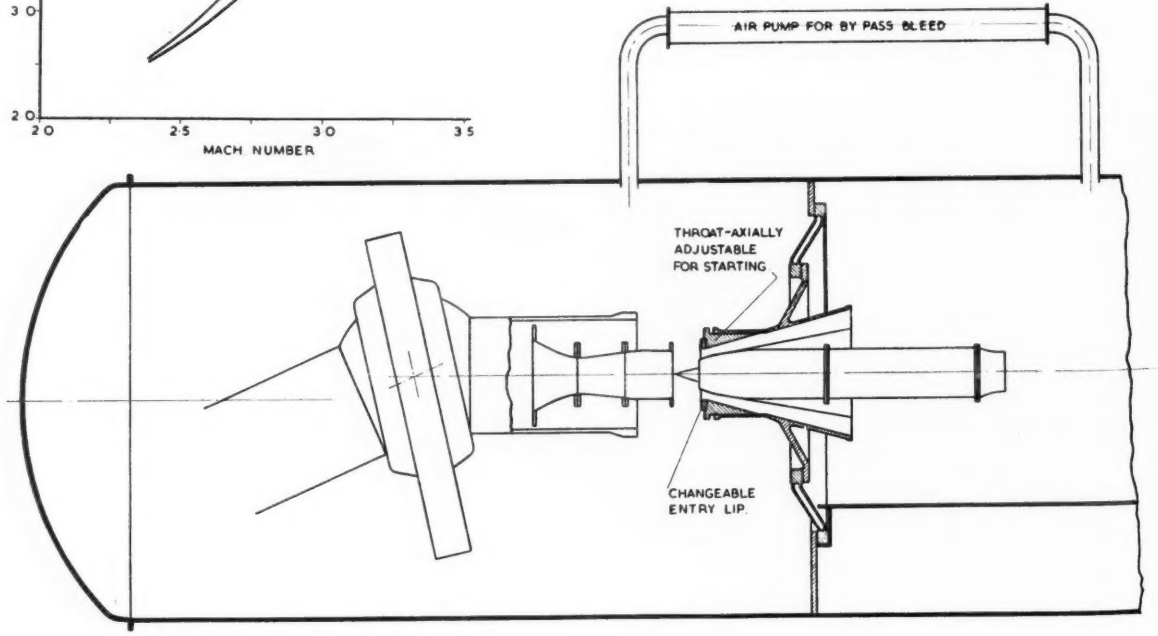


FIGURE 18. Arrangement and performance of a free jet spill diffuser.



Ram-jet flight testing confronts the research engineer with an agonising dilemma. He is not producing an article for regular use under defined conditions; he must try new things, test their capabilities and his understanding, and let practice sharply teach him right and wrong. In ram-jet research trials human lives are not at stake, although human reputations possibly are, and every engine in ballistic trials is destined for loss on return to sea level; one is therefore uniquely free in every trial to reach the limits of failure in performance or mechanical operation. Each flight should carry graduated risks of several different kinds to explore extremities in many aspects of design and operation. The art is to arrange that any total failure will be due to the last risk taken. But logic never rules; conscience must sometimes yield to the prejudices and necessities of life. One must put up an occasional dull success to buy time for a batch of intriguing failures.

Figure 19 shows the test vehicle used by N.G.T.E. for flight trials. It was first designed at N.G.T.E. and has since undergone continuous development at the hands of the Establishment and Messrs. D. Napier and Son Ltd., by whom it is manufactured. Its objects were to try out combustion, fuel control, cooling and intake techniques in flight, to confirm, deny or extend ground results and, above all, to throw up the working problems of application and keep research and development on a realistic basis. The flight envelope chosen was speeds up to $M = 2{\cdot}5$ and heights up to 60,000 to 65,000 ft.

It began as a dart of 600 lb. weight launched by four forward wrap-round boost rockets weighing 800 lb. to a launch speed of $M = 1{\cdot}55$; a light, cheap system. This arrangement was made to work, but uneven thrust decline of the separate boost motors led to excessive pitching of the dart at boost separation, with attendant protest by range staff and loss to us of control of the required flight trajectory. It now flies with eight rear wrap-round boosts of 1,800 lb. weight in a lengthened version of 950 lb. weight to the higher launching speed of about $M = 1{\cdot}75$. The vehicle is about 20 ft. long and 18 in. overall diameter. The front is a steel shell comprising intake and ducting spanned by a flat centre body housing fuel, pumping and control gear, instrumentation and radio transmission apparatus. The rear is a steel monococque carrying stabilising fins, boost, combustion unit, liner and nozzle. A total of about 30 launches has covered many aspects of the design and operation of engine components and of the vehicle and its equipment as a flying tool. Besides many small but important details of construction and operation, the major test variations have included:

(1) Two radically different boost separation techniques.

(2) Five fuel system stages, starting with gas pressurisation and constant fuel flow, first adding ignition flow control, then mixture control for acceleration; later substituting pressurisation by an air turbine-pump with speed control, and finally substituting a two-stage fuel system with cruise thrust and flight speed control.

(3) Four combustion chambers with successively improved standards of thrust and altitude performance.

(4) External and submerged wall cooling systems.

(5) Three instrumentation layouts.

(6) Three intake and exhaust area configurations giving different overall engine characteristics.

(7) Four trajectories and durations, or sets of flight operating conditions.

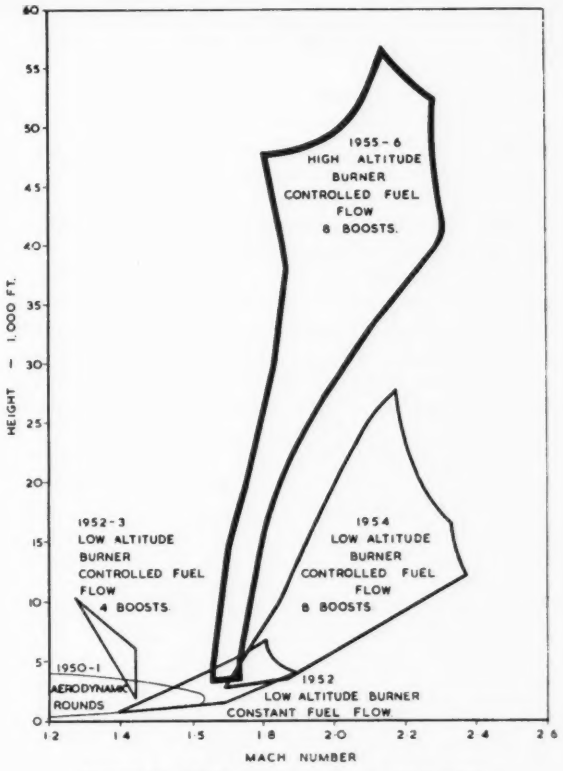


FIGURE 20. Flight envelope of test vehicle trials.

In fact, roughly one major change per flight was made to the engine, the vehicle, the equipment or the flight envelope, and each one was equivalent to roughly ten permuted flights on the shot-gun technique. This can only be done by treating each trial as an elaborate, specialised affair based upon the sum total of previous data and experience, to be followed by detailed study of the flight records and intensive ground checking of any observed flight peculiarities. One can then leap-frog economically over groups of issues together. It calls for flexibility and unnatural forgiveness in drawing offices and shops, but these virtues our associates at Luton possess.

Regrettably, one trial was a perfect, unblemished success; obviously we picked too easy a target and wasted a round. In eight trials we did a little better; they too were evident successes, but we found a few useful private snags. Another ten were tolerable

compromises and of the rest, five were really fine failures stimulating streams of enquiry, speculation and invention.

Figure 20 shows the record of speeds and heights covered so far. By arithmetic it seems that on average height has increased at 2,000 ft. per trial and speed at 0·03 M—dare we assume that another fifteen trials will get us near $M=4$ at 90,000 ft.?

The uses of a test vehicle need continuous debate, although it should be remembered that the profits are sometimes unexpected ones. This vehicle has regularly, sometimes irregularly, operated at the higher ram temperatures and pressures, Mach numbers and degrees of supercritical operation which we are only now able to achieve on the ground. This certainly added confidence in ram-jet capabilities and drew attention to points of design or operation needing further study in full scale or model test rigs. But this particular qualification is now lost for this particular vehicle with recent rapid improvement in ground test equipment. It also confirmed that ground simulation techniques for the complicated dynamic process of ignition, especially at supersonic speeds, were reasonable guides to flight performance. It has forced some clearer thinking on the effects of high transient "g" on fuel system operation. It taught a sharp lesson on the sources and cumulative performance effects of small air leakages in light construction. It taught the practical limitations of the most efficient boost techniques and sponsored some understanding of the complicated kinematics of the process. It made us learn how to install electronic equipment to work in the pressure and vibration field of the engine. It has confirmed many combustion, control and cooling techniques, but especially, it has forced the habit of precise accounting of these matters over the whole field of operation, rather than the sweeping generalisations on performance and operating factors into which research too easily slips.

This type of vehicle chiefly solves functional problems. With the experience now gained, and we hope, most of these lessons learnt, and possessing new versatile ground test equipment, the utility of ballistic trials is rapidly decreasing. Further progress turns upon variable geometry, internal compression intakes and so on, and emphasises intricate problems of control and endurance, requiring accurate observations of a more scientific pattern. But it must be asked, will it all be worth while?

Figure 21 attempts to vivify the real point of a ram-jet as a true aircraft engine. In a climb at the modest E.A.S. of 500 m.p.h. it shows the decrease of fuel load and the patterns of aircraft drag and engine thrust. It presumes a reheated turbo-jet for speeds up to about $M=2·0$ and a variable intake ram-jet thereafter; the two engine thrust characteristics match remarkably well. Moreover, the intake and exhaust area requirements are the same for both engines at the transition speed. The intake and exhaust systems can therefore be shared and in principle the ram-jet combustion system could be used as the reheat system of the turbo-jet. Two vital points are, the roughly constant thrust characteristics of the ram-jet which behaves in climb and acceleration like a super-efficient rocket, and the large excess of available thrust over cruising drag. For little extra weight over normal take-off power plant requirements, the ram-jet can "tack-on" to the take-off engines and deliver the aircraft promptly to guaranteed speed and height, irrespective of likely aircraft weight and drag variations. By closing the exhaust nozzle at top speed the cruising s.f.c. drops to about 2·5, representing a modest 40 per cent overall engine work efficiency compared with the target of 50 per cent suggested earlier.

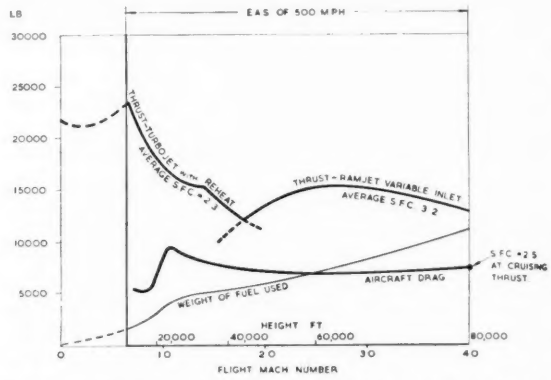


FIGURE 21. Thrust and drag patterns of a hypothetical aircraft. A.U.W. 50,000 lb.

Reflecting on the fuel consumption pattern it seems that unreheated turbo-jets, or rocket derived engines with s.f.c. of 4·0 or more, if used as alternative take-off engines, are unlikely to cancel respectively their extra engine weight or fuel consumption during climb. In descent or stand-off the ram-jet-turbo-jet combination could operate as a plain turbo-jet with adequate thrust and good economy.

The ram-jet has outgrown the uncertainties of youth and confidently seeks new and challenging enterprises. If high cruising speed and operating height are wanted, the ram-jet is willing and able to serve. But for purely economic flight it would be naive not to recognise that high engine efficiency is useless if it can only be achieved at flight speeds involving prohibitive loss in lift drag ratio or structural efficiency. In the flight example given it is the drag characteristic which most needs improvement. Perhaps this will come from variable wing geometry, or part-ballistic flying, or structural and aerodynamic integration of engine and airframe. The end point of ram-jet development and the greatest prizes it offers will only be achieved by a drastic change in aircraft convention.

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DISCUSSION

Dr. E. S. Moult (Chairman, *Fellow*): This excellent and interesting paper had given some glimpse of future possibilities and the proper sphere of operation of the ram-jet. The success of the ram-jet depended on the forward speed of flight and, as the Mach number rose, the ram-jet came more and more into its own. While waiting for speeds to advance, the gas turbine engineer impatiently placed a ram-jet in the blast of the turbo-jet's exhaust. This was called "reheat," but the principle was the same and the augmentation very important. Without doubt this development of after-burners had assisted in solving combustion problems in ram-jets: now, in return, the work on ram-jet intakes—diffusion, velocity distribution, pressure recovery and stability—would pay a valuable dividend in the application of supersonic intakes to the gas turbine engine. At the highest speeds of flight air-breathing engines tended towards a common denominator and this was already seen in the arrangements for intake and exhaust.

In the early days Mr. Probert and his team had worked under great difficulties and many restrictions in the way of test facilities. It was greatly to their credit that they did so much with so little at that time. Whether Mr. Probert was now designing better ram-jets to fit the new facility, or extending the facility to accommodate the better ram-jets was, perhaps, a little obscure to the outside observer!

Dr. R. R. Jamison (Assistant Chief Engineer—Ram-jets, Bristol Aero-Engines Ltd., *Associate Fellow*): This was an extremely important subject for, in the ram-jet engine they saw the epitome of high speed air-breathing propulsion units for airborne flying machines. They had been shown a vista leading to aeroplanes flying within the earth's atmosphere at speeds conceivably up to a Mach number of 4 or 5 or more.

It was most fitting that Mr. Probert should be giving this lecture, for from small beginnings he and his associates had been laying the groundwork for major advances into hypersonic propulsion. It was also most fitting that this main lecture of the Society should be associated with the first section of the Society created under its charter, the Guided Flight Section, for in ram-jet propulsion they had a subject which formed a connecting bridge between the conventional aeroplanes of today and the widening realm of aeronautics and astronautics gathered under the collective title of guided flight. Guided flight was a general term which was intended to imply all that was covered by the conceptions of automatic flight and control of aircraft and even space craft. Guided missiles was a branch of that division and they could say that the recent development of ram-jets owed a great deal to guided missiles, which not only furnished a user of these engines ahead of the requirements of manned aircraft, but also provided a means for their rapid development in flight testing, because with these expendable missiles some controlled, some ballistic, but all employing means of communication and control peculiar to guided flight, they had been able to mount experiments which could not be contemplated with a human pilot involved. Some of the misbehaviours of supersonic engines reached catastrophic proportions because the ram pressures which they got in the ram-jet engine and the dynamic pressures on an aeroplane at supersonic speeds were of the order of what were commonly regarded as boiler pressures, so if one got, as one could, with pulsating combustion, reversals of thrust 50 times a second, plus or minus 100 per cent, one could see that the system did not last very long. This of course pointed a warning to what would happen if one did not have completely reliable units in supersonic aircraft; again he was speaking generally of air-breathing engines.

Up to the present time the ram-jet had suffered a great deal from the blanket of security. For with its close and hitherto narrow association with military weapons, little had been disclosed on the nature of this power unit, and the great amount of work which had gone to bring it to practical reality and, by the same token only a privileged few had been brought into contact with the people engaged on this work. They in the Bristol engine department had had this privilege and had seen how Probert and his team at N.G.T.E. had, with slender resources, brought a most successful research enterprise into being, and still found time to help others with their problems. None-the-less he thought that Mr. Probert would agree that the work done so far had only brought the ram-jet to the threshold of its career and greater fields still lay before it.

With the very advanced and extensive test equipment now coming into use at Pyestock the way was opening up for a real assault on the problems of supersonic propulsion and in this connection a most significant change was seen in the process of aircraft engine development, for as the speed of flight rose, the problems of testing the engines became as great or greater than those of the development of the engines themselves. The Pyestock contribution in this field also, had been most important in the design of their engine test facility and the research work put into the supersonic nozzle and spill diffuser techniques. As had been shown, by the use of these spill diffusers, pressure ratios for blowing supersonic nozzles could be greatly reduced by factors of six or so; this made a tremendous difference to the cost of development. In his view all future important advances in high performance air-breathing engines would require support by equivalent advances in the technique of testing them. So the design and development of test plant would be a most important branch of aeronautical engineering and this factor must be budgeted for in the logistic planning of future work. He thought it was clear that this was only lately appreciated and really not in time; all the ram-jet development which had been done in this country, or certainly since he had been on the job (seven years) and probably before, had suffered from the late arrival of the necessary test plant and they had had to push forward by this "suck it and see" technique in flight which had

certainly been more expensive and slower than it need have been.

The question of resources raised the question of where and how far they were going in this quest for high performance in air-breathing engines. It was apparent that the cost was going to be high and there had been signs recently that people were now seriously counting the cost they might have to pay. He thought that they must remember that man himself was an air-breathing engine, who was generally well advised to keep within the earth's atmosphere. For a long time to come they would find that man would find occasion to transport himself and his goods about the earth's surface. There was, and he thought there would always be, a premium on doing this as rapidly as possible; throughout his history man had been willing to pay for greater speed. He firmly believed this trend would continue in the aeroplane field both for civilian and military purposes; and this country could not afford to drop out. If they did not do it, others would and that could have most serious repercussions for this nation which had traditionally depended on selling transport among its methods of finding a living. Thus they must press on with the research and development in the field surveyed by Mr. Probert, for it was clear that there was still a path ahead on which concrete achievement could be confidently predicted, if they put forth the effort. The lecture had shown clearly that the way ahead from the air-breathing engine side could be accurately foreseen, there were no technical difficulties of a major nature which development could not handle. The picture with the aeroplane, he thought in this case, was slightly more complex because, particularly if it were an inhabited aeroplane, the question of thermal heating at very high speeds would be a major barrier. It had become a cliché in technical circles to call the ram-jet a simple form of engine. Some people tended to lay such emphasis on that that they had lost sight of the fact that in its own speed range it was an extremely effective one; people liked to dismiss it as the apocryphal flying stove pipe. This had caused some embarrassment because some quite eminent people had been unable to see why such a simple object should need such costly development. Well, it was a flying stove pipe fundamentally, but it was some stove! A unit of the size of the ram-jet discussed, the N.G.T.E. design, would have a power output in thrust horsepower and fuel flow equivalent to that of a good size Naval Destroyer, or about a twenty thousand ton passenger liner. The means for pumping and for regulating automatically and burning this flow of fuel in the furnace had all to be done within the stove pipe, and to achieve this duty efficiently and reliably in the wide range of operating conditions possible in the ram-jet was a measure of the technical problem.

In his work in this field he had found most intriguing the great width and range of interests in ram-jet technology; one had basically a simple engine with its fuel supply system and which apart from a variable nozzle had no moving parts. None-the-less to achieve success in this branch of engineering had required intimate study and experimentation and knowledge in a wide number of fields ranging from supersonic aerodynamics to the vibrations, and servo-controls, and including the heavy engineering of the test plant. This stemmed from the inward nature of a ram-jet in which they had a gas dynamic system in which the relatively determinate problems of the mechanical components of a rotating engine had been exchanged for the less tangible but more temperamental behaviour of wave motions, boundary layers and turbulent flow fields in a gas system accompanied by intense chemical reaction. In other words, as every engine designer knew, all the ingredients for *trouble!*

Now with such a high specific energy through-put—they were talking in terms of tens of thousands of horsepower in engines weighing two or three hundred pounds—it needed the diversion of only a small percentage of this energy into vibration or heat flow to give the development engineers plenty to do; vibration problems could be severe and the destruction swift and, the same applied to misplaced heat.

Against this background of the nature of the practical problems they could measure the achievement of Mr. Probert and his team at the National Gas Turbine Establishment and their associates at Napiers in making some very real and useful progress in this difficult art.

He would like to comment on the lecturer's scale of success in flight trials. It was published in the printed paper, and although the lecturer did not refer to it, there could be no more graphic delineation of the philosophical difference between research and development. At Pyestock they could emerge triumphantly from the tangled shambles of an experiment with the battle cry so familiar on the firing ranges, "well . . . we learnt a lot." And they could still feel they had enhanced the lustre of their reputation. Those who had to make engines for service use had found it much harder to get this accepted by their customers and found it impossible to convince them that the interest of the results transcended the need for immaculate reliability. So, he wondered if he were complimenting the lecturer if he told him, what he sincerely believed that, in his own words, the lecture was a "perfect unblemished success," or should he conclude with the claim to perfect success himself (in truly scientific form) that his contribution was "a really fine failure stimulating streams of enquiries, speculation and invention?"

Mr. Probert: The collaboration between Dr. Jamison's team at Bristol and Pyestock had been so close and of such long standing that it seemed almost a family party to meet here and find himself discussing this sort of problem with him. None-the-less he was glad to be able to use this occasion not only to thank Dr. Jamison for these present remarks, but also to acknowledge the effort and initiative contributed at Bristol in the development of this whole subject.

Of course he was not suggesting that a missile engine should be judged on the same yardstick as a research instrument, but he certainly was proposing for the latter that it was best to try to demonstrate successively new

things just once, even by the skin of one's teeth. His yardstick was perhaps the hardest to get accepted, both exercises were difficult and appropriate in their spheres.

P. J. Cooper (Engineer (Gas Dynamics and Fuel Metering) D. Napier and Son Ltd., *Associate Fellow*): He would like to thank Mr. Probert for the skilful effort of realignment which, it was hoped, would make the climate of this work very much easier. They had always felt that the management had been puzzled because there were two yardsticks of success; one was record heights, record speeds, and so on, and the other was the balance sheet. Working for the establishment they had discovered that the height records, speed records, and similar achievements were accompanied by fairly small financial rewards whereas the magnificent failures were accompanied by a lot of work which, of course, brought in the money. They were glad to know that Mr. Probert had re-defined their definition of success to correspond with the financial result.

In Fig 2 of the paper on the 1,100°K line the specific fuel consumption went to rather frightening values with smaller nozzle throat sizes. Now they, who had been accustomed to dealing with the internal flow of the engine and leaving the external flow to the aerodynamicists, tended to expect that the specific fuel consumption would go down. He thought the answer was contained in the fact that some element of external drag was deducted from the thrust to deduce the net thrust. For smaller nozzles the mass flow through the ram-jet was reduced and, therefore, the thrust was reduced. If, from that, one took a substantially constant drag, naturally the remainder diminished very rapidly. The specific fuel consumption based on that particular net thrust showed an alarming rise towards the left-hand side of the diagram; but in fact this net thrust was that left over from the engine to propel the rest of the aeroplane. With increasing supersonic speeds, cruising at very low combustion temperatures, the size of the engine in relation to the aeroplane became so large that some form of integration probably became essential. If so, then the drag of the engine was indistinguishable from a very high percentage of the total drag of the aeroplane, so that in plotting a specific fuel consumption on this basis, he wished to suggest that it was important to deduct from the ram-jet only the drag which decreased the overall lift-drag ratio of the aeroplane. Any drag which formed part of the normal lift-drag ratio of the aeroplane should not be deducted from the net thrust used to calculate specific consumption. This, if taken to extreme lengths, suggested an all-wing, all ram-jet aeroplane of a delta form with all its payload carried internally and all the drag arising from this flying wing. In level cruising flight the net thrust in Fig. 2 was then zero and the specific consumption infinite.

A second point was the out-moding of test vehicles. When a large test plant of the type now installed at N.G.T.E. was built, the information which would be obtained from it in the next few years was just the information required to design it in a thoroughly satisfactory manner when the idea was first put on paper, so perhaps it was possible, without offence, to suggest that defects in service might appear in operational tests. Leaving aside the extrapolation which was done from a possibly unwarranted assumption to a possibly unjustifiable conclusion that the ram-jet test vehicle could reach a Mach number of 4 at 90,000 ft. in 15 more rounds, it was quite clear from Mr. Probert's project study that the potentialities of the ram-jet test vehicle, even with a Pitot intake, had been very much in advance of what one would have been able to predict when the programme first started, in that it had flown at a Mach number of 2·5 when the accepted theory of the time that Pitot intakes were no good at Mach numbers above 1·5. There was, he thought, therefore a strong case for the test vehicle as a pointer to the accuracy of one's knowledge of the requirements that one should test on the ground. The existence of a test plant, however powerful, could never completely replace the value of popping one off into the air occasionally.

Mr. Probert: He should have made it clear, as he tried to do briefly in the written paper, that the net thrusts in Fig. 2 did contain a subtracted wave and friction drag consistently estimated, that the particular drag assumptions made did, in part, determine the shapes and values of the curves illustrated and that, in practice, particular cases of concern must be studied in detail to find the best design. Fig. 2 was therefore merely a self-consistent example chosen to illustrate the general pattern of thrust and economy and, perhaps more importantly, the role variable inlet and exhaust geometry could play in improving engine characteristics. Where therefore, as at the lower left and right corners, the results were clearly sensitive to the assumptions, it was especially evident that the particular results selected must not be regarded as a general case. The drag values implicit were typical of those associated with the engine alone. If a varying fraction of the aircraft drag could be "lost" in the engine by adjustment of engine design then different shapes of curve would follow, but presuming an inescapable drag, due to lift, the extreme case postulated by Mr. Cooper could not arise. The real point was that depending on the method of drag accounting used, a high "specific" fuel consumption did not necessarily mean a high absolute fuel consumption or low overall efficiency.

Dr. W. F. Hilton (Chief Aerodynamicist, Sir W. G. Armstrong Whitworth Aircraft Ltd., *Fellow*): They had tested several supersonic intakes in their wind tunnel at Coventry and had encountered the phenomenon of buzz. It was quite a striking phenomenon which could be heard quite clearly above the noise made by the wind tunnel. Could the lecturer comment on the effect of off-design operation, which stimulated buzz, on the combustion. Of course one realised its effect on the fatigue life of the highly stressed aircraft structure, but he wondered if it were likely to interact with the flame and put it out.

Communicated: He would also like to comment on the use of ram-jets for satellite vehicles, as mentioned

by a later speaker, who extrapolated the supersonic climb at $M=4$ beyond the limits intended by Mr. Probert. He would like to ask that due allowance be made in such calculations for the reduced amount of aerodynamic lift required to sustain a vehicle at a constant altitude above the earth's curved surface. Lift was no longer equal to weight for steady flight, and was only 97 per cent of the weight at $M=4$. Above $M=15$ this effect would enable a ram-jet to fly very much higher than might otherwise be expected, as shown in Table I of his paper at the High Altitude and Satellite Rocket Symposium in July 1957.*

Mr. Probert: Buzz was primarily a thing to avoid, rather than to cure, and one reckoned one rather missed one's aim if one ran into it; but to answer the question specifically, if the intake did surge then in most cases the combustion chamber would probably go out. This was not a universal rule, it depended a great deal on length factors, on the inherent stability of the combustion chamber itself, on the height, in other words it depended how near the limits of the combustion chamber were whether the strength of the disturbance caused by buzz would or would not put the engine out. He did not think there was any rule, in general he thought it would put the engine out, but not necessarily.

On the point about aerodynamics and its proper use in the engine design, he could speak at some length and with some conviction on that, because he wished they knew of some aerodynamics which could be used. He had said in the written paper that the design of the external shock system of the engine was really one of the easier parts of the whole business. The internal interference factors were very powerful indeed and while people would readily explain that this shock interfered with that boundary layer and directed this air this way and distributed that air over there, there were never any numbers to it and often no real orders of magnitude and they in the engine side of it would be only too pleased to use any aerodynamics or any aerodynamicists who offered any of this exact kind of information. They could take that as a challenge if they liked!

Could Dr. Hilton explain, could Dr. Hilton tell him how, in anything other than clumsy terms such as putting in the little dodges he was referring to, they might control the distribution factors in intakes? He was sorry to press Dr. Hilton so hard, but he might have an equally fighting reply!

R. F. Sargent (Bristol Aero-Engines Ltd., *Associate Fellow*): He would like to comment first about the size of plant necessary for developing ram-jets. It had been shown that without the vast air supplies and test bed facilities such as those at Pyestock, a ram-jet could not be run on the ground. While this was true it needed stressing that this limitation did not set aside the ram-jet as a comparatively difficult or expensive supersonic engine to develop.

Rotating engines for supersonic application could be run on test beds without the aid of powerful air supplies or exhausters but only under strictly limited conditions. Any air-breathing engine which might possibly compete with a ram-jet must be ground tested under the same conditions and would need test facilities of equal size and capability. The possession of rotating parts did not simplify or eliminate any of the development testing problems of the ram-jet but tended to create others.

Ram-jets were the first truly supersonic engines to utilise the large facilities at Pyestock because, among their other attributes, they were the easiest of the supersonic air-breathing engines to design and test. The ground testing techniques now being developed in conjunction with ram-jet development would be available for other types of power installations when they became available for ground test development.

His other point referred to the necessity for variable intakes and nozzles. The optimisation of a ram-jet over a range of Mach numbers, say, from a Mach number of 2 to $3\frac{1}{2}$ called for an exit nozzle with variable throat area which, in turn, required an intake of varying capture area. (Fig. 2 of Mr. Probert's paper showed how at $M=2$ a smaller intake area was required than at $M=3{\cdot}5$). It was a fortuitous coincidence, however, that the conical centre-body intake had a capture area whose variation with Mach number could closely resemble that required. Very flexible ram-jets could, therefore, be designed without the complication of variable geometry intakes.

Mr. Probert: It was perfectly true that the turbo-jet at high supersonic speed had all the problems of the ram-jet and more besides and the rather advanced type of ground equipment they were speaking of earlier was indiscriminately of value and assistance to both engines. It was perfectly true he thought, perhaps more true, to say that in the long run the turbo-jet, being more complicated, might even be more dependent on its use for successful development.

He had suggested that the conical intake did lend itself with a variable nozzle to efficient use over quite a wide speed range; this was true as Mr. Sargent had underlined. But it was not always possible to get the whole area variation they would like, and there was, of course, an inclined flow before the intake below design speed due to the fact that the physical intake area was not changing. The actual capture area was changing and there was a difference between the capture area and the actual intake leading to a drag, not a big term but it was discussed in the paper. He thought that the engine type Mr. Sargent meant was one of the types he himself meant in speaking of his class 2 engines.

S. W. Greenwood (College of Aeronautics, *Associate Fellow*): He would like to compliment Mr. Probert on the very stimulating presentation of his material. The ram-jet was an engine whose characteristics were not as widely understood as they should be, and he agreed with the Chairman that they had heard a paper which was due to become a classic. In presenting his material Mr. Probert had rendered a very great service to the

*To be published by the Royal Aeronautical Society.

Society and indeed to the aeronautical field as a whole. Those charged with the job of educating people in propulsion systems had the problem of getting information across to people that would still be useful to them when they came to work on the systems. There was little security unclassified engineering data available on the ram-jet, and the lecture had put into his hands material for two or three very good lectures. He was prepared to say that something like one-third, or possibly more, of the real engineering data on the engine that he could make available to students had been contained in the lecture that evening. In this connection he would like to point out that the lecture delivered on the same subject by Dr. Jamison to the Derby Branch of the Society* about a year ago constituted perhaps something approaching one of the other thirds.

He was interested in the rather cautiously expressed philosophy of the place of the ram-jet in the future of aviation that Mr. Probert presented. He showed that if they were prepared to consider systems involving two power plants, and that was something which he thought they were coming more and more to accept as time went by, the ram-jet showed great promise when combined with the gas turbine. This scheme was being tried already by the French in the Leduc series of aircraft where the pilot took off on gas turbine power and it was intended that ram-jet power should be used at high speeds.

Dr. Jamison had mentioned the word "Astronautics." He was very happy indeed to hear it at a meeting of the Royal Aeronautical Society. He did not think that there was any doubt that their Society, through the Guided Flight Section and in other ways, was taking an increasing interest in astronautics. A question that arose there, he thought, was this: The ram-jet was a high speed propulsion engine, and while the upper "limit" to the speed range that they had been looking at that night had been at about a Mach number of 4 or possibly a little higher, one was tempted to consider the possibilities of the ram-jet breaking into the very high speed flight range. A vehicle in circular orbit around the Earth travelled at a speed equivalent to about a Mach number of 20 in the atmosphere. That was a lot higher than a Mach number of 4, but what was to stop them extending the speed range above a Mach number of 4 and thereby competing more directly with the rocket and its very high specific propellant consumption?

Mr. Probert: Considering all the trouble one went to in writing this paper he was sure that Dr. Jamison was glad that it was Mr. Greenwood who was carrying on giving more lectures.

On the point of the higher speed prospects of the ram-jet he had endeavoured to keep the discussion down to speeds of four because until $M=4$ he did not think there were really any special difficulties or fresh principles, besides he thought the worst difficulties would always be the getting of equipment on which to carry out development. With higher Mach numbers one did begin to require, presumably, fuel cooling of internal surfaces, one ran into extreme dissociation problems, and he did not really see how the ram-jet was necessarily going to maintain this desirable self-accelerating characteristic at those very high speeds. He would say he would be very uncertain of the prospects over a Mach number of 4. There were troubles with the theory but also some attractive possibilities and certainly an attractive single-speed performance, but whether or not this was a realistic system with the flexibility which was required of an engine he personally was in doubt.

E. L. Goldsmith (Royal Aircraft Establishment): He thought that Mr. Probert was quite right when he said that there were no methods of estimating accurately what happened to velocity distributions in, or at, the entry to combustion chambers when the intake was operating with swallowed shocks in the so-called supercritical condition. It was possible to calculate where an assumed final normal shock was inside the intake, but this did not approximate to what was actually happening. There was, in fact, a complicated series of shocks, expansions, and breakways, and that was what gave rise to the bad velocity distributions. The answer really was some form of boundary layer control which would clean this area up; this was probably weighty and complicated and so, as Mr. Probert said in connection with buzz "the best thing to do is to avoid it," and he would put in a plea for doing this, by adopting the forms of variable geometry of the nozzle and the intake so that the intake itself did operate in its most efficient or critical condition without these swallowed shocks and their attendant troubles.

*Ram-jets. R. R. Jamison. *Journal of the Royal Aeronautical Society*, June 1957.

Temperature Distributions in Aircraft Structures and the Influence of Mechanical and Physical Material Properties*

by

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SUMMARY: Thermal effects in aircraft may arise from kinetic heating, engine installations and auxiliary systems. The first source is potentially of greater importance, although problems in connection with the second source can be severe, especially with vertical take-off aircraft of the "flying bedstead" type. The difficulty encountered in a formal analysis of heat conduction problems when practical boundary conditions are to be satisfied frequently suggests a finite difference approach. This may take the form of direct numerical integration or the use of digital or analogue computers or network analysers in which electrical circuits are arranged to be analogous to the thermal system. Several examples illustrating the use of these finite difference methods are instanced, such as the growth of temperature in a thick plate, the transient distribution of temperature in a rib carrying a hot duct; the chordwise distribution of temperature and transient loss in torsional stiffness in a thin wing due to kinetic heating, and the distribution of temperature and spanwise thermal stress due to kinetic heating in a bay of an integrally stiffened panel. The importance of experimental methods is emphasised and a brief description and illustration of a model fuel tank for simulated kinetic-heating tests is given. An urgent plea is made for correlated data on thermal contact resistance of typical aircraft joints, some examples of which are also illustrated. Data is given on some physical and mechanical properties of materials likely to be used for airframes where thermal effects are expected. These include thermal expansion, conductivity, diffusivity, creep, fatigue, specific strength and stiffness, and a parameter called here the "Thermal Stress Efficiency."

1. Introduction

The advent of the jet engine towards the end of the Second World War has introduced, both directly and indirectly, a mushroom growth of thermal problems in the airframe. The need to fly high for fuel usage economy necessitates internal heating for the pilot, crew and passengers of the subsonic aircraft, while some form of external heating is required to prevent or disperse ice formation. In addition the actual jet efflux introduces local airframe and engine heating problems. Then again, the greater thrust development of the jet engine has made possible aircraft speeds at supersonic levels, thus reversing the previous problem of internal and external heating to cooling to combat kinetic effects. The problems arising from this latter effect may be acute and our present knowledge of heat transfer, thermal stressing, and temperature properties of materials is limited, particularly as new materials are constantly being developed. To some extent, however, the earlier problem of heating the aircraft has given a lead to the solution of the cooling problem as they are somewhat complementary, albeit at opposite ends of the thermometer.

Thermal distributions in aircraft structures induce stresses from thermal gradients and from different coefficients of expansion if different materials are used. These effects may be short term, as in the case of a fighter with a supersonic burst, or a supersonic missile and involve variation with time; or long term, as in the case of a supersonic transport aircraft, involving a near thermal equilibrium condition, although the type of aircraft quoted here will also have distinct transient thermal problems. Apart from these considerations, the temperature properties of the materials used will have a profound influence on the strength and stiffness of the structure. The actual design criteria for the various parts of the airframe structure will depend upon the role of the aircraft, its shape and manoeuvres, and may involve thermal stresses, stresses at temperature, creep, thermal fatigue, and thermal buckling.

To estimate the magnitude of thermal stresses it is necessary to determine the temperature distributions and these involve either an exact solution of the basic differential equation or, a solution employing a method of finite differences. This latter may demand the use of computational aids such as digital computers, analogues, and so on. Exact solutions are only possible for simple systems and it is therefore apparent that, for a complete structure involving a wide combination of structural elements and various heat sources and sinks where the method of finite differences *must* be used, the problem entails the solution of a large

*Presented at the Joint Conference of the Institute of Physics (Stress Analysis Group), and the Royal Aeronautical Society held at Cranfield, 19th September 1956.

number of difference equations. For example, in a recent vein of optimism an attempt was made to investigate the temperature distributions in a complete airframe with clearly defined heat sources. The analysis yielded about 100 simultaneous first order differential equations and the project was abandoned so that sanity might be preserved.

It may, therefore, be seen that great importance must be attached to the thermal testing of structural elements and complete structures. This, however, again poses acute problems in the reproduction of heating conditions similar to those to which the actual aircraft is subject, and in the measurement of temperature, stress, thermal coefficients, and so on. Rate of heating assumes particular importance in this context.

Analogue methods have an important part to play in heat transfer problems and the use of photoelastic methods may be a possible source of solution, particularly for investigating thermal effects on castings, forgings, solid fittings and, possibly, thermal buckling.

NOTATION

T_{AW}	adiabatic wall temperature
T	temperature
γ	ratio of specific heats of air
r	recovery factor
M	Mach number
h	coefficient of heat transfer
ε	emissivity of skin surface
B	Stefan-Boltzmann constant
α	absorptivity (solar) of skin surface
Q	solar radiation constant
ϕ	incidence of solar radiation
a	thermal diffusivity
σ	thermal stress
E	Young's modulus
a	coefficient of linear expansion
k	thermal conductivity
w	thickness of skin or plate
x, y, z	distances referred to Cartesian co-ordinates
t	time
G	shear modulus
J	St. Venant torsion constant
ρ	density
f_{ult}	ultimate tensile strength

Suffices

1	refers to ambient conditions
s	refers to external skin conditions
m	refers to spatial increment
n	refers to time increment
i	refers to internal skin conditions

Constants

$\beta, p, A, B.$

2. Sources of Heat on Aircraft

2.1. KINETIC HEATING

The source of kinetic heating is now well known. It arises from the heating of the air in the boundary layer by rapid acceleration due to viscous friction and stagnation at high speeds. The variation of the maximum structural temperature with Mach number in the stratosphere over the Arctic region, neglecting radiation, is shown in Fig. 1 and can be obtained from the following relationship:—

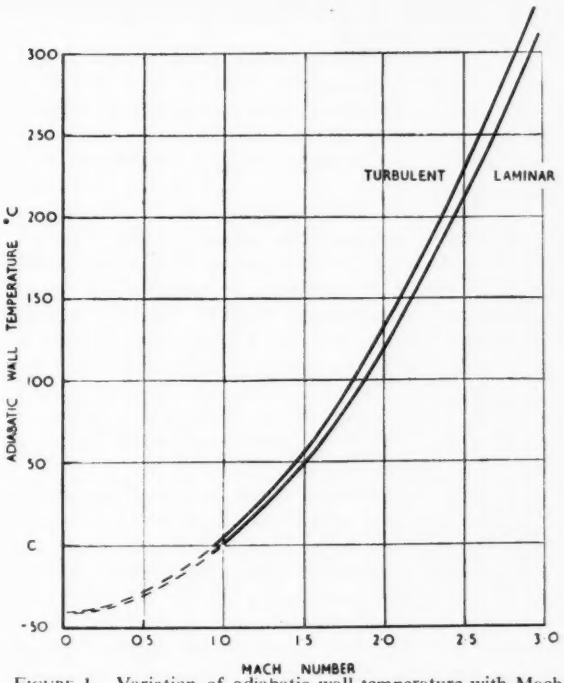

FIGURE 1. Variation of adiabatic wall temperature with Mach number in the stratosphere over Arctic regions.

$$T_{AW} = T_1 \left(1 + \frac{\gamma - 1}{2} rM^2\right)$$

$r \simeq 0{\cdot}85$ for laminar flow
$r \simeq 0{\cdot}9$ for turbulent flow.

It is important to note, however, that the small amount of actual flying evidence suggests that at the higher speeds the actual temperature may be lower than theory.

At very high altitudes (above 60,000 ft.) the effect of solar radiation must be included. The variation of maximum temperature with Mach number can then be deduced from:—

$$h(T_{AW} - T_s) - \varepsilon B T_s^4 + \alpha_s Q_s \cos\phi = 0.$$

It is probable that these altitudes will be associated with hypersonic flight employing rocket propulsion or ballistic missiles.

Stresses in a structure arising from kinetic heating may be both transient and steady. Both will involve temperature differentials but the former will vary with time and are of particular importance with guided missiles and fighter aircraft, whereas the latter represent the equilibrium or "soaked" stage and are of particular importance for long range transport or bomber aircraft. The two effects must be distinguished from the material viewpoint since it is possible to use materials under transient conditions that would break down completely under equilibrium conditions. For instance, a guided missile may use aluminium alloy or polyester impregnated glasscloth plastic efficiently at say a Mach number of 3, whereas both of these materials would be

extremely inefficient for the structure of a bomber aircraft at this speed.

The effect of saturation temperature on aircraft structure weight is demonstrated in Fig. 2. This shows its influence on a multi-cell type wing structure designed on strength requirements and clearly indicates the marked effect on aluminium alloy compared with steel and titanium alloy.

The input of heat into the aircraft is influenced by the materials used and may depend on the ingenuity with which radiation, conduction, and convection effects can be employed to advantage. Obviously the use of heat resistant materials and coatings will help, as also will sandwich forms of structure, such as honeycomb, which make use of the excellent heat resistance of air. The amount of weight that can be spared for insulation must, however, be balanced against the weight of cooling systems used to obtain the optimum combination for minimum weight.

Calculations show that where a reasonable aircraft duration is required it is extremely weighty to attempt complete insulation using heat resisting materials. It is therefore necessary to introduce cooling systems located at the important parts of the aircraft where required. These, in general, will be cockpit, cabin, instruments, bomb or other armament stores, radomes and radar gear, and possibly fuel tanks and fuel, although the fuel will provide an effective heat sink.

2.2. ENGINES

Apart from heating problems in the actual engine parts, reciprocating engines provide few heating problems on the aircraft structure, the main one of these being the possible effects of the exhaust gases both in the structure containing the exhaust manifold and the local structure around the exhaust exit. The advent of the jet engine has, however, tended to increase the severity of elevated temperature problems. These are again associated with the structure surrounding

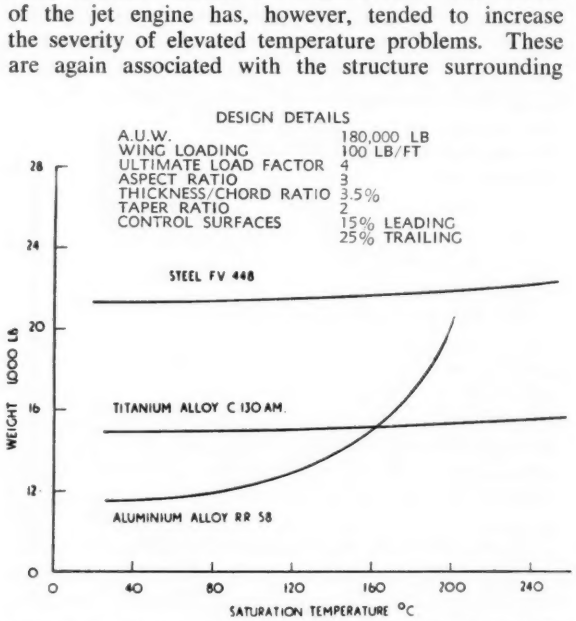

FIGURE 2. Variation of optimum weight of straight multicell boxes designed on strength requirements with temperature.

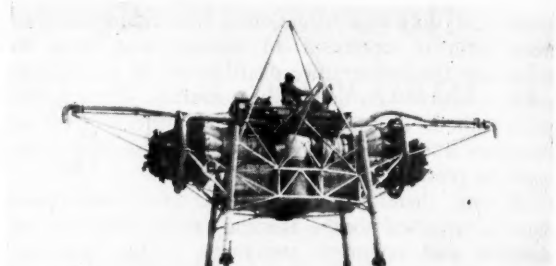

FIGURE 3. The Rolls-Royce "Flying Bedstead."

the jet pipe and the influence of the jet efflux, but as the temperature and the velocity of the exhaust gases are now appreciably increased there is the danger of the heat zones being extended to other parts of the airframe such as flaps, bomb doors, fuselage sides, and even tail units. So far the problems have not proved so severe as originally suspected and it has generally been within the capabilities of the light alloys to cope—however, it has, in some instances, involved increase in sheet gauge and structural scantlings to compensate for the reduction in strength and stiffness arising from heating effects from the jet engine and also to avoid excessive thermal buckling. Probably the most effective way of combating heating problems from this source is by very careful attention in the early design stages of the aircraft, particularly with regard to engine positioning, coupled with effective insulation of the jet pipe.

The heating problems take on a very different aspect, however, when the jet engine is used to provide effective aerodynamic lift rather than for propulsion only. The aircraft concerned is popularly called a "vertical take-off" aircraft, although it may include both propulsion and vertical thrust providing a forwards and upwards take-off of very short length. Early experiments in this field were made by Rolls-Royce Limited. Their now well known "flying bedstead" shown in Fig. 3 clearly illustrates all the essential ingredients for a V.T.O. aircraft. The lifting engine is located at the c.g. and, to provide control in pitch and roll, the control jet system is incorporated involving the conveyance of bleed air from the compressor at fairly high temperature and pressure through a ducting line to exit nozzles—the resulting thrust being variable in direction and magnitude. Thus a V.T.O. aircraft has an appreciable heat source at its c.g. and further heat sources along the fuselage and wings in the form of the control ducts. An additional factor aggravating this heat problem is that the total vertical thrust must at least equal the weight of the aircraft and hence 20 lifting engines would not be an uncommon number for an aircraft of medium size. In addition to the actual heat sources within the V.T.O. aircraft there is the problem of the reflection of

hot gases from the jets on to the structure of the aircraft when on the ground before rising. The use of elevated platforms may ease this problem but these may not always be available for all operations required from a V.T.O. aircraft, particularly in the military sphere.

2.3. AUXILIARY SYSTEMS

Other heat sources on aircraft include anti-icing systems and heating systems which generally involve the ducting of hot air up to about 180°C at low velocity and pressure, although if bleeds from the engine compressors are employed then conditions near the engines are severe.

Anti-icing systems, of course, provide the reverse problem from kinetic heating in that the interior of the structure, usually confined to the wing and tail unit leading edges, contains hot air ducts to prevent icing of the outside skin. There is no doubt that the heat transfer problems involved here have at least provided some information to aid the solution of kinetic heating problems, as they involve the effect of temperature on material properties and stresses, and buckling arising from thermal gradients in the structure. With recent developments of electrical heating the problem tends to become much more localised to the skin itself.

Cabin heating systems present much the same problems but on a less severe scale than the V.T.O. control duct system, although effective insulation to avoid excessive heat loss is of immense importance since the surface areas involved are very large, *e.g.* the fuselage cabin of a transport aircraft.

Apart from cabins, heating systems are required for bomb cells, instruments, and windscreen demisting. The latter presents a difficult problem in preventing crazing or cracking of the toughened glass or plastic due to thermal differentials.

All these problems of course may turn to one of cooling for supersonic aircraft, although even then a weather eye must be kept open for flight conditions that may entail low temperatures.

3. Temperature Distribution in Structures

3.1. GENERAL METHODS

In spite of the enormous amount of work put into the solution of problems of heat conduction since the time of Fourier, the aircraft engineer finds that his particular idealised, but practical, problems have received little attention until recent years. This is particularly so with transient state conduction, and in the equilibrium state when two or three dimensions are involved. This is probably due to the fact that formal analytical solutions to practical problems, where they are possible, can be so complex as to involve more computing time than the less elegant solution obtained by a method of finite differences.

Briefly, this difficulty of solution arises from the necessity to allow for a coefficient of heat transfer at a surface or more than one surface if, say, the structure is cooled internally, and from the necessity to make adequate allowance for discontinuities such as abrupt change of shape, contact resistances between structural

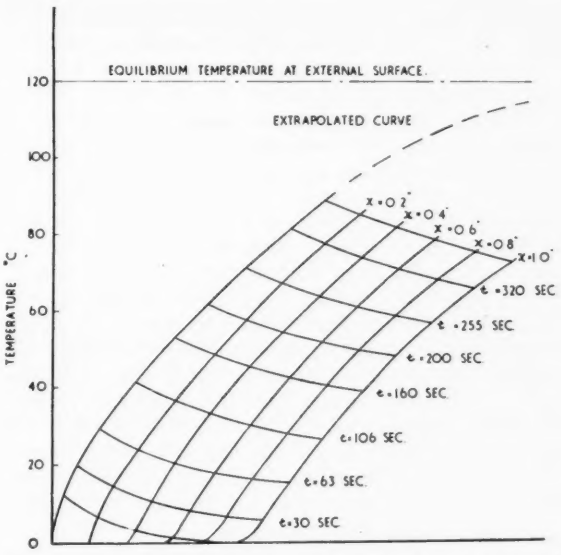

FIGURE 4. Growth of temperature in a titanium plate heated on external surface and cooled on the other.

members or between some form of external insulation and the structure.

The transient-state temperature distribution due to uni-directional heat conduction in a solid is described by the partial differential equation

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t}$$

when the thermal properties of the solid do not vary.

Replacing these differentials by finite differences leads to the equation:—

$$T_{m,\,n+1} = T_{m,\,n} + \beta\,(T_{m-1,\,n} - 2T_{m,\,n} + T_{m+1,\,n})$$

where $T_{m,\,n}$ is the temperature at a point m spatial intervals from zero at an instant n time intervals from zero,

$$\text{and} \quad \beta = \frac{\alpha\,\delta t}{(\delta x)^2}\ .$$

A well-known stipulation is that for a given spatial interval δx, the time interval δt must be chosen so that the modulus $\beta \leqslant \frac{1}{2}$ so that the numerical steps taken in the solution may be stable. In regions where the rate of variation of temperature with time is uniform, numerical work may be decreased by taking groups of "p" time intervals. Here the finite difference equation becomes:

$$T_{m,\,n+p} = T_{m,\,n-p} + 2\,p\,\beta\,(T_{m-1,\,n} - 2T_{m,\,n} + T_{m+1,\,n}).$$

This method was used to determine the growth of temperature in a titanium plate heated on one side and cooled on the other.

Heating corresponds to suddenly accelerated flight from a Mach number 0·95 to 2·5 and 60,000 ft. over Arctic regions, and cooling corresponds to natural convection (upwards) to kerosine. The partial temperature distribution in the plate is shown in "carpet" form in Fig. 4. To determine the curves shown in the figure by the method of finite differences required about

25 man-hours. This partial solution represents about one-third of the work necessary to enable a justifiable extrapolation of the constant position curves to be made to their asymptotes.

To economise in time the engineer may resort to digital or analogue computational aids in applying finite difference methods, or he may use a direct electrical analogy in the form of a thermal analogue or network analyser. The direct analogy technique appears to be especially attractive in view of the fact that eventually, for accurate prediction of kinetic temperature distributions and their effects, it will probably prove necessary to take account of the variation of the kinetic heat transfer coefficient with structure surface temperature, chordwise and even spanwise position, and time in the form of a flight-path history. Perhaps it is not looking for too much to hope that account could be taken of the variation with temperature of such properties as conductivity and specific heat. It is significant that the development of thermal analogue techniques is proceeding apace.

The feeling at present, with regard to the accurate determination of thermal stress, appears to be to determine the temperature distribution by calculation or by measurement in the case of a highly complex heat transfer system and to calculate the thermal stress from it. However, in a complicated system, the number of points at which it is necessary to determine the stress level may become so large as to be prohibitive and prove to be an economic factor in favour of model techniques.

3.2. EXAMPLE OF TEMPERATURE DISTRIBUTION IN A WING

Rib Carrying a Heat Source

The use of digital computers in solving transient state heat conduction problems is illustrated in the following example. Fig. 5 is a schematic representation of the trailing portion of a rib in a wing with unstiffened cover skins. Passing through the rib and bolted to it is a duct carrying hot air travelling at fairly high speed. The problem was to determine the transient distribution of temperature in the structure for a duration of fifteen minutes starting when the hot air flow began. The structure and the associated air spaces were split up into a number of elements as shown in Fig. 6. It should be mentioned that such a small number of elements as shown can only give a coarse representation of the temperature distribution, but the available data, especially for contact resistances, did not justify a more refined investigation. The masses and the positions of the centres of mass of the conducting elements were calculated and the resistance to heat flow from one element to an adjacent one was determined by converting the depth of flanges to a mean thickness for each element and proceeding in the normal way for one-dimensional steady-state flow. In effect, this assumes that heat transfer takes place for a short time (δt) without change of temperature, and that the elements are sufficiently small for the two-dimensional heat flow to be assessed with reasonable accuracy by adding the effects of one-dimensional heat flow estimated in each of the two directions. The heat transferred by radiation from the duct to the enveloping box was determined by assuming that the duct rose rapidly to a temperature very near that of the hot air flowing through it, and that the scatter due to reflection from the inside of the box distributed the radiated heat uniformly over the surface. In this way a single curve was established to represent the relationship between the radiant heat from the duct and the temperature of the receiving surface.

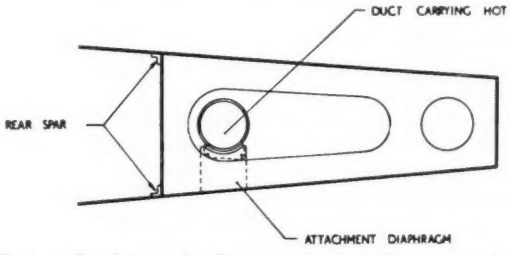

FIGURE 5. Schematic diagram of wing rib carrying hot air duct. Material: Light alloy.

Linear approximations were made to this curve and to a similar curve representing the heat transferred by natural convection to the air space around the duct, to facilitate solution of the final equations. The process lead to a set of eleven simultaneous first order differential equations of the type

$$\frac{dT_6}{dt} + 32{\cdot}6T_6 - 0{\cdot}354T_1 + 0{\cdot}06\,(T_2 + T_3 + T_4) - 1{\cdot}55T_5 - 1{\cdot}55T_7 - 21{\cdot}5T_{11} - 744 = 0, \text{ and so on,}$$

which were solved with the aid of a digital computer taking $\frac{1}{8}$ minute time intervals. The results are shown graphically in Fig. 7. The temperature of element 2, particularly, reached a level not normally permissible in a load-carrying light alloy component, so insulating bushes were interposed between the duct and the attachment point at the rib. Possibly the resistance of the interfaces would reduce this level of temperature appreciably; but in the absence of reliable data the worst case, *i.e.* no resistance, was assumed. The representation of the system is too coarse by far to make a worthwhile attempt at calculating thermal stresses.

3.3. AN EXAMPLE OF TEMPERATURE AND STRESS DISTRIBUTION IN A TYPICAL INTEGRALLY STIFFENED PANEL

Another example involving kinetic heating relates to a symmetrical part of a stringer bay of an integrally stiffened titanium panel. It is perhaps of interest to

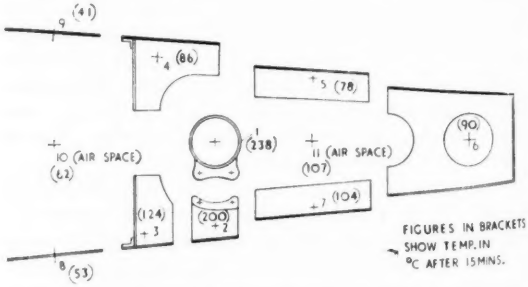

FIGURE 6. Schematic representation of wing rib showing elements chosen.

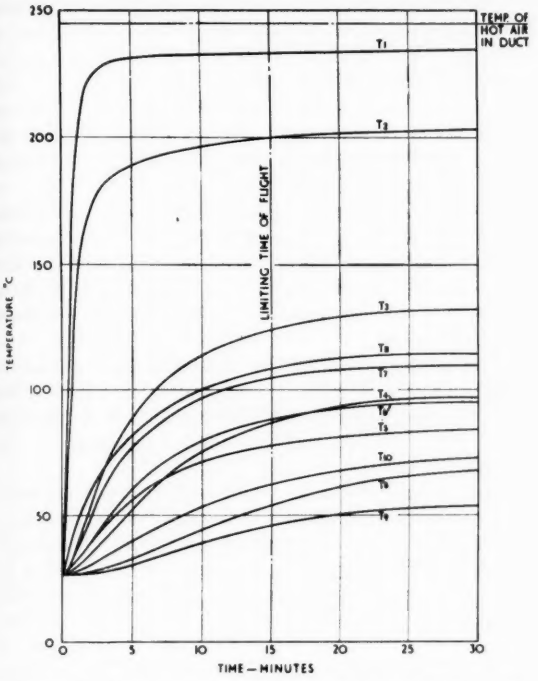

FIGURE 7. Variation of temperature with time for various elements of rib.

note that the use of integrally stiffened skin structures for supersonic aircraft can present worthwhile weight advantages over the more generally accepted multi-cell construction for thickness to chord ratios down to about 4 per cent or so. Hence the temperature distribution and subsequent stress distribution for integrally machined panels is of considerable interest.

The panel corresponds to a position 5 ft. from the leading edge on the undersurface of the straight wing of a fighter type aircraft, and heating corresponds to suddenly accelerated flight from a Mach number of 0·95 to 2·5 and 60,000 ft. over the Arctic. Here the adiabatic

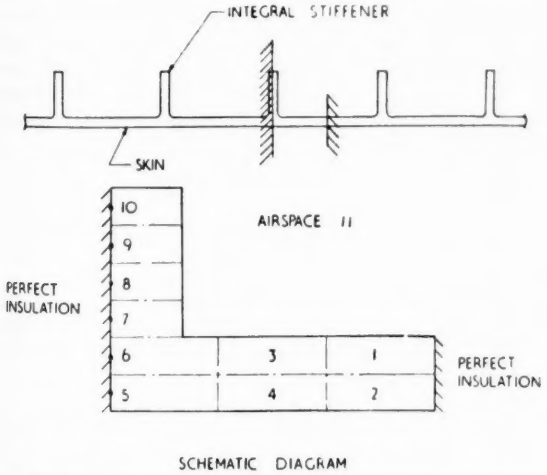

FIGURE 8. Temperature distribution in integral construction.

wall temperature is approximately 220°C. Figure 8 shows the blocks into which the system was split for solution with the aid of an analogue computer. The shaded edges signify perfect insulation and correspond to planes of symmetry. A typical equation is:—

$$\frac{dT_1}{dt} + 10{,}860T_1 - 10{,}850T_2 - 11{\cdot}3T_3 - 2{\cdot}94T_0 = 0,$$

and so on.

The solutions obtained from the analogue computer are shown graphically in Fig. 9.

The difference between the temperatures of the pairs of blocks in the depth of the skin, for example between T_5 and T_6 is of the order of 3°C (max.) and so the mean temperatures of the three pairs of blocks 1, 2 and 3, 4 and 5, 6 have been shown in the figure.

The maximum temperature difference between the outside skin and the inner end of the integral stringer was 134°C after two minutes and 92°C after four minutes. It is interesting to reflect that at this latter time the aircraft would have travelled 114 miles.

The spanwise thermal stresses in the bay were determined by the method used by Schuh[1], namely

$$\sigma = Ea\,(T_1 - T_n + A).$$

A is a constant, determined for each instant of time by equating to zero the algebraic sum of the thermal loads produced by the elements so that no spanwise external forces exist.

Thus $$A = \frac{\Sigma\,(T_n - T_1)\,\delta x.\,\delta y.}{\Sigma\,\delta x.\,\delta y.}$$

For both the temperature and stress distribution the initial temperature of the panel was taken as 0°C. Fig. 10 shows the temperature and stress distribution in the system at the instant when the tensile thermal stress in the end of the stiffener is maximum (approximately 10,000 p.s.i.), and the distribution at the instant when the compressive thermal stress in the skin is maximum (approximately 12,000 p.s.i). It should be remembered that these figures have been determined assuming sudden acceleration from $M = 1{\cdot}0$ to $M = 2{\cdot}5$, and so represent the worst case. The largest thermal stresses were found to be tensile occurring towards the end of the

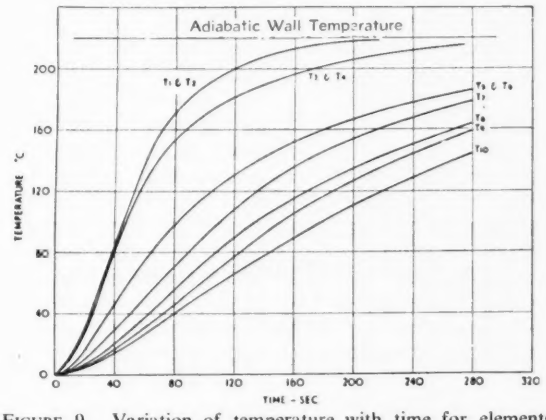

FIGURE 9. Variation of temperature with time for elements of bay of integral panel. (Solution by analogue computer.)

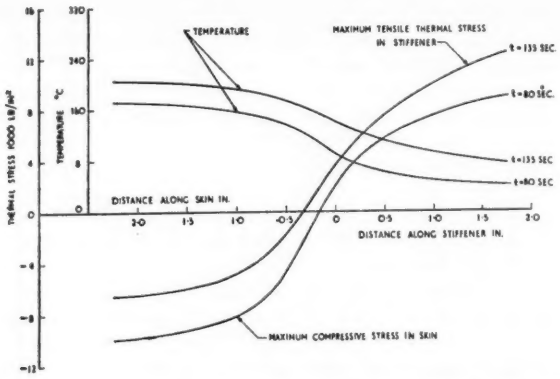
TEMPERATURE
MAXIMUM TENSILE THERMAL STRESS IN STIFFENER
t = 133 SEC.
t = 80 SEC.
t = 135 SEC
t = 80 SEC
DISTANCE ALONG SKIN IN.
DISTANCE ALONG STIFFENER IN.
MAXIMUM COMPRESSIVE STRESS IN SKIN

FIGURE 10. Distribution of temperature and spanwise thermal stress in stringer bay of integrally stiffened panel.

stiffener. This might have been anticipated from the work of Parkes[2].

The order of compressive stress in the skin illustrates clearly the importance of transient thermal effects, especially when it is borne in mind that supersonic aircraft may dive to attain high supersonic speeds and that the pull-out may take place at a time when compressive stresses in the upper surfaces of the wings are large.

The temperature distribution in the above system was also determined by the Electrical Research Association using a network analyser. Here the relevant conduction equation is:—

$$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}=\frac{1}{\alpha}\frac{\partial T}{\partial t}$$

with the boundary conditions as follows:—

$$\frac{k\partial T}{\partial x}=-h_s\,(T_{AW}-T) \quad \text{for external surface of the skin}$$

$$\frac{k\partial T}{\partial x}=-h_i\,(T-T_i) \quad \text{for internal surface of skin}$$

$$\frac{k\partial T}{\partial y}=-h_i'\,(T-T_i) \quad \text{for internal surface of stiffener}$$

$$\frac{\partial T}{\partial y}=0 \quad \text{for the faces where perfect insulation was assumed owing to symmetry.}$$

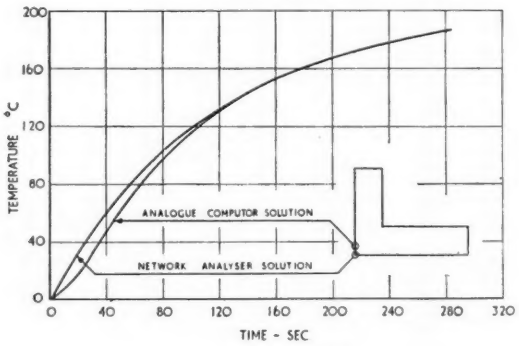

FIGURE 11. Comparison of results from analogue computer and electrical network methods.

The temperature of the internal air space was determined from

$$\text{(Thermal capacity)}\quad \frac{dT}{dt}=\int_{\text{int. surface.}} h_i\,(T-T_i)$$

where h_i and h'_i are the heat transfer coefficients to air due to natural convection from horizontal and vertical surfaces respectively.

A comparison of the solution by the two methods is shown in Fig. 11 where temperature-time curves are drawn for (*a*) a point on the external surface of the skin opposite the stiffener, taken from the network analyser results, and (*b*) the element (5) taken from analogue computer results.

The apparent discrepancy between the two curves in the initial parts is due to thermal lag which arises from the heat capacity associated with the element for which the solution was obtained by means of the analogue computer.

It is of interest to know the whereabouts of the maximum temperature gradients since these alone cause thermal stresses in an unrestrained homogeneous material. Fig. 12 shows the points considered in the solution by network analyser. The maximum temperature gradients and the time at which each occurs are shown on the diagram. The arrows show the direction of heat flow. It should be noted that the gradients shown for branches (4)—(5), (5)—(6), (11)—(18), (18)—(25) are of doubtful value as a result of the abrupt change from fine to coarse mesh.

3.4. EXAMPLE OF CHORDWISE DISTRIBUTION OF TEMPERATURE AND STRESS, AND LOSS OF TORSIONAL STIFFNESS IN A THIN WING

If laminar flow cannot be maintained over a substantial portion of the leading edge of wings, the chordwise variation of heat transfer coefficient may lead to compressive stresses near the leading and trailing edges causing an appreciable loss of torsional stiffness in very thin wings. This effect is more pronounced in a missile-type wing, where no leading edge controls are incorporated, than in the more

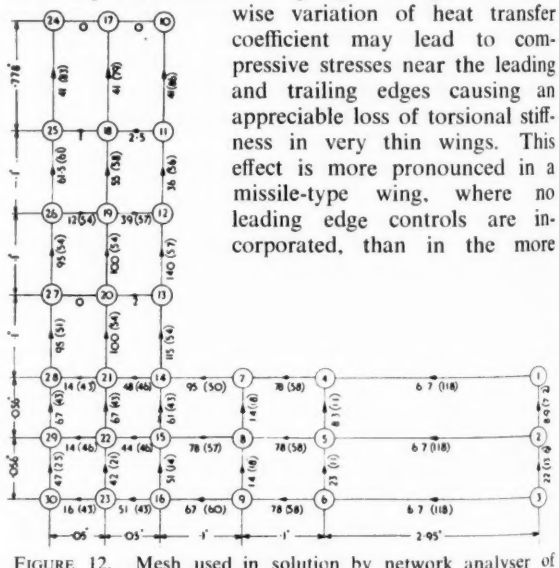

FIGURE 12. Mesh used in solution by network analyser of transient temperature distribution in integrally stiffened panel. Figures indicate maximum mean temperature gradients °C/in. and the times in seconds at which they occur (in brackets). Arrows show the direction of heat flow.

conventional supersonic aeroplane wing where the chordwise distribution of heat transfer coefficient is fairly uniform in the region of the structural box. To illustrate the order of severity of the problem, consideration has been given to a hollow titanium wing with 0·25 in. skins, a 36 in. chord, and a thickness to chord ratio of 3·0 per cent. The calculation of the heat transfer coefficient was based upon suddenly accelerated flight to $M=3{\cdot}0$ and 50,000 ft. over Arctic regions. The chordwise distribution was obtained by assuming no laminar flow near the leading edge, and by extrapolating the curves given in the Royal Aeronautical Society data sheets such that the heat transfer coefficient rose to a high value at the stagnation point.

The problem was then simplified to that of a flat plate heated on one surface, the relevant equation of conduction and boundary conditions being:—

$$\frac{\partial^2 T}{\partial x^2}+\frac{h}{kw}(T_{AW}-T)=\frac{1}{\alpha}\frac{\partial T}{\partial t}$$

$$T=340^\circ\text{C}, \quad x=0, \quad t>0$$

$$T=0, \quad x>0, \quad t=0$$

$$\frac{\partial T}{\partial x}=0, \quad x=0, \quad x=36 \text{ in.}$$

$$T=340^\circ\text{C}, \quad t=\infty,$$

where x is distance along plate from leading edge.

The conduction equation was replaced by the finite difference equations:—

$$V_{m,\,n+1}=(V_{m+1,\,n}-2V_{n,\,n}+V_{m-1,\,n})\frac{\alpha\,.\,\delta t}{(\delta x)^2}+V_{m,\,n}\times \times\left(1-\frac{h\alpha\,.\,\delta t}{kw}\right)$$

and

$$V_{m,\,n+p}=(V_{m+1,\,n}-2V_{m,\,n}+V_{m-1,\,n})\frac{2p\alpha\,.\,\delta t}{(\delta x)^2}+V_{m,\,n-p}\times \times\left(1-\frac{h2p.\,\alpha.\,\delta t}{kw}\right)$$

where $V=(T_{AW}-T_{(x,\,t)})$, and solved numerically for the particular plate concerned.

Two typical distributions of temperature are shown in Fig. 13. This figure demonstrates the marked temperature variation in the early transient stage. The ringed values are points calculated by ignoring the effect of heat conduction in the plate and confirm the validity of this simplification originally used by Budiansky and Mayers[3].

For various chordwise distributions of temperature in the plate the spanwise thermal stresses were determined from the relationship

$$\sigma=E\,a\,(A+Bx-T_{(x)})$$

and A and B are constants determined from the two requirements that the external end load and bending moment shall be zero, namely:

$$\Sigma_x\,(A+Bx-T)\;\delta x=0$$

and $$\Sigma_x\,(A+Bx-T)\,x\delta x=0.$$

It was found that the maximum compressive stress near the leading edge was about 19,000 lb./in.^{2} occuring

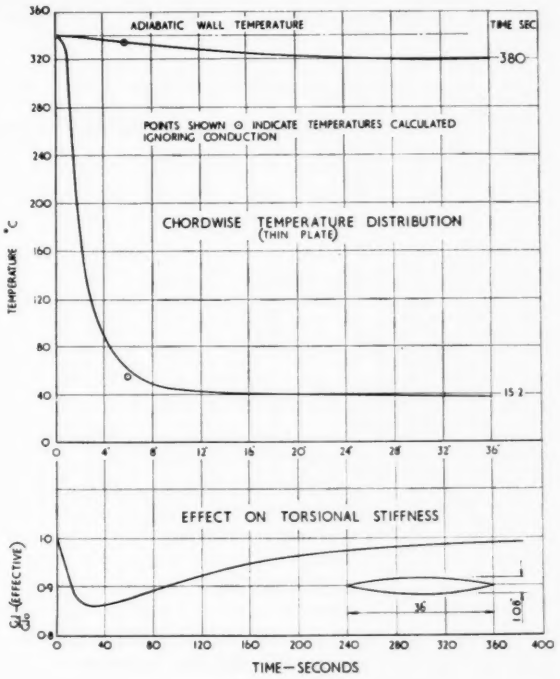

FIGURE 13.

after about 30 seconds. This induced a maximum tensile stress of about 3,000 lb./in.^{2} at the trailing edge.

From the thermal stresses the ratio of effective torsional stiffness to the initial torsional stiffness was determined for various time intervals from the expression

$$\frac{GJ_{EFF}}{GJ_{(0)}}=\frac{1+w\Sigma_x\sigma r^2\delta x}{GJ_{(0)}}$$

where r is the distance from the axis of twist. The variation of $(GJ_{EFF})/(GJ_0)$ with time is also shown in Fig. 13. It may be seen that a maximum loss of stiffness of 13·5 per cent occurs at 30 seconds. It seems unlikely that this loss of stiffness will be much modified by the conduction of heat within the wing during the periods of acceleration to speed which may reasonably be expected. Internal structure will worsen the problem if an appreciable decrease of thermal capacity occurs near the leading edge, although this will be offset by the use of solid wedge-like leading edges.

3.5. COOLING PROBLEMS

In a practical aircraft, heat sinks, both natural and manufactured, must exist since there will be definite temperature limitations at various points in the aircraft necessitating cooling. For example, radio and electrical equipment is limited to 60°C and the cabin to 30°C. The existence of these additional heat sinks will not introduce any basic changes to the methods outlined previously for the determination of temperature distributions and it is possible to envisage a complete solution to a complete structure with a number of heat sinks and sources by the superposition of a number of independent calculations with suitable thermal coupling.

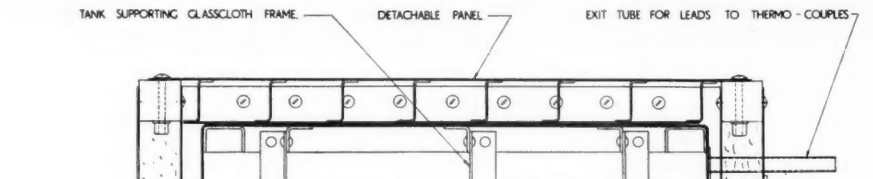

FIGURE 14. Section through model fuel tank.

The problem of cooling necessitates the determination of heat flows so that an accurate assessment may be made of the overall heat balance for the aircraft. This demands a knowledge of the various heat transfer coefficients involved and there is a whole field of unknowns here which require immediate practical determination.

It may be mentioned in passing in this brief reference to cooling that the use of the aircraft fuel as a heat sink appears to be a practical proposition for Mach numbers up to about 2·5 or so. Other methods utilise Vortex tubes with water evaporator units, film cooling and transpiration cooling. Both the last methods appear attractive, particularly as they can involve a reduction in skin friction coefficient.

3.6. PRACTICAL HEAT EXPERIMENT ON A FUEL TANK

As already mentioned, one important problem on a supersonic long range aircraft is the heating of the fuel by kinetic heating. The fuel will act as a heat sink and in this way assist the cooling problem, but the maximum temperature in the fuel is limited by the risk of explosion or fire. The calculation of the temperature rise in the fuel is difficult, partly from the factors already discussed, but mainly by the lack of accurate data on the various heat transfer coefficients for the various combinations of materials and the form of airframe construction adopted. A practical experiment has therefore been initiated at Shorts to investigate this problem. Unfortunately the test results are not yet available but brief details of the work are given here. Fig. 14 shows a section of the tank. It is approximately cubic in shape and represents a typical fuel cell. The fuel is contained in a hycatrol bag tank. The sides of the tank are insulated to prevent outward flow of heat, although a thin stiffened metal lining is incorporated to provide simulated titanium web sheeting heat paths. The top and bottom are detachable panels so that various forms of structure can be investigated, *e.g.* steel, titanium, honeycomb, and so on. In this case the construction is a titanium riveted skin and stringers and is representative of what may be used on a long range supersonic aircraft. Thermo-couples in the fuel are mounted on a resin impregnated glasscloth laminated frame inside the hycatrol tank and additional thermo-couples are located on the skin and stringers. The primary object of the test is to obtain the distribution of temperature in the fuel with time, the limiting safe fuel temperature being considered to be 150°C, at atmospheric pressure in the presence of air. It is intended to compare this with a theoretical analysis as a check on the various assumed heat transfer coefficients, and so on. Later experiments on this tank will investigate the effect of different forms of structure for the top and bottom panels.

Figure 15 shows the calculated rise in mean temperature of the fuel in a tank with similar significant

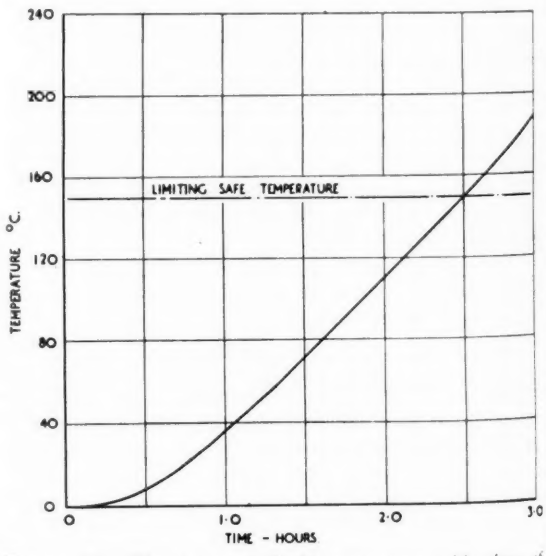

FIGURE 15. Rise in mean fuel temperature with time of flight of long-range $M = 2{\cdot}5$ aircraft.

dimensions as the model previously discussed. It is assumed that steady flight at a Mach number of 2·5 and 60,000 ft. lasts for three hours and that during this time the fuel is used continuously down to 10 per cent of full capacity. It should be mentioned that one-dimensional heat flow and negligible contact resistances have been assumed for the purpose of the calculation. Actually, the two-dimensional flow which takes place will tend to increase the heating of the fuel but this will be off-set by the contact resistances.

4. Mechanical and Physical Properties

4.1. MECHANICAL PROPERTIES[4]

4.1.1. *Strength and Stiffness*

The growth in aircraft speed and weight, coupled with general reductions in wing depth for aerodynamic reasons, demands considerable increase in strength while aeroelastic effects, particularly transonic flutter and supersonic aileron reversal, can become critical in design. In this respect plan form plays a very important part, *e.g.* a relatively high aspect ratio straight wing at supersonic speeds may well be designed almost entirely on stiffness, while a low aspect ratio sharply swept delta supersonic aircraft may be designed entirely on strength. The importance, therefore, of stiffness as well as strength cannot be over-rated.

Figure 16 indicates the variation of ultimate specific strength with temperature for various materials. Generally it may be seen that light alloys have superior specific strength at room temperature but their properties fall off rapidly above 150°C or so when titanium alloys become very efficient. Above 450°C steel begins to overtake titanium.

Figure 17 presents the variations of specific stiffness with temperature. Generally at room temperature the specific stiffness values are closer together than corresponding strength values but steel has rather better stiffness than titanium throughout the temperature range.

4.1.2. *Creep*

Creep is a property that is receiving marked attention for airframes subjected to elevated temperatures.

Figure 18 presents some typical creep data for typical aluminium alloys, titanium alloy, and steel. Due to lack of actual data the values in brackets have been extrapolated. Rapid reduction in the creep strength of these materials occurs in the temperature ranges 100-200°C, 200-300°C and 400-500°C respectively, and for supersonic aircraft suggest that severe creep problems may be encountered from a Mach number of 1·5 upwards in light alloys, from 3 for titanium and 4 for steel depending, of course, on the creep life expectation for the aircraft.

4.1.3. *Fatigue*

Fatigue is undoubtedly becoming more severe with the advanced aircraft designs. The source of fluctuating loads on aircraft is primarily from high frequency, low velocity gusts, or from cabin pressurisations. Increase in speeds leading to higher design stresses and the need to fly high for jet economy obviously aggravate the situation.

Figure 19 shows the fatigue strength trends of various materials at room temperature. Practically no fatigue data exists at elevated temperatures but indications are that actual endurances are increased with increasing temperature. This sounds good but of course the main problem of thermal fatigue arises from temperature stresses from repeated thermal gradients. It is encouraging to note, however, that the most promising materials for supersonic applications, that is steel and titanium, have appreciably better room temperature fatigue properties than the light alloys.

4.2. PHYSICAL PROPERTIES

4.2.1. *Thermal Conductivity*

For long range supersonic aircraft where some form of internal cooling is involved, the equilibrium or steady state of heat flow may be applied with good accuracy. In this case it is the thermal conductivity of the structure that will determine the temperature gradients, thermal

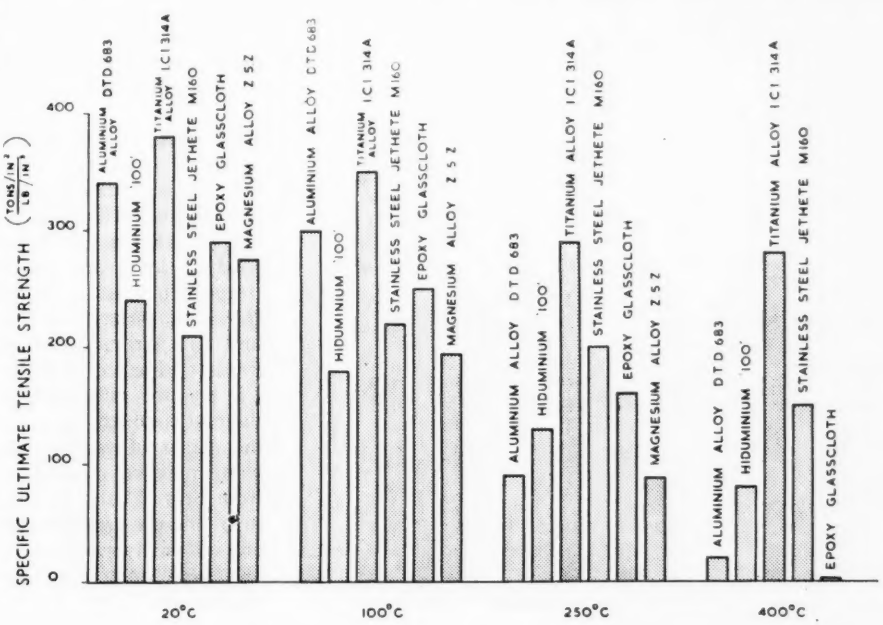

FIGURE 16. Material strength plotted against temperature.

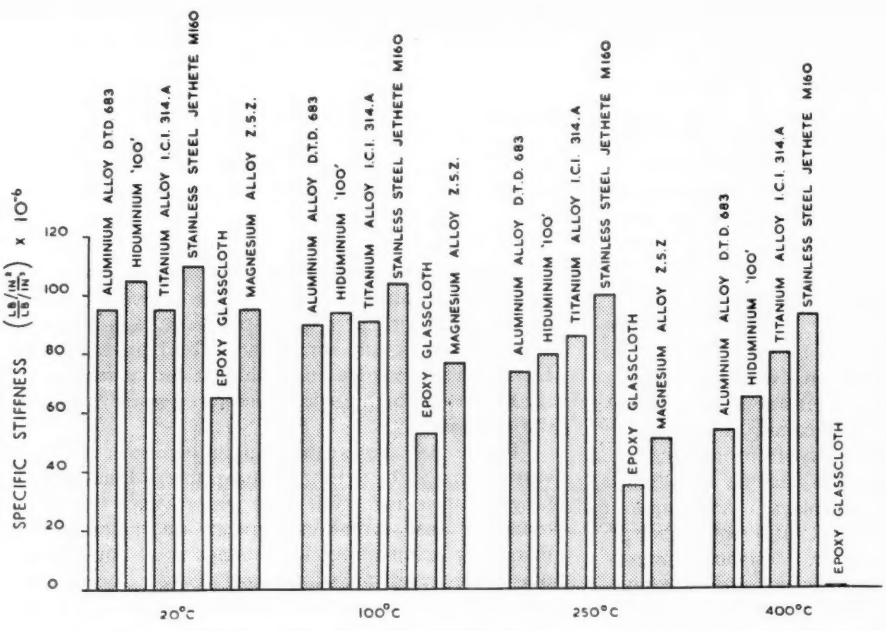

FIGURE 17. Material stiffness (E) plotted against temperature.

Alloy	*Ratio of Stress to Produce 0·1% Creep Strain to U.T.S. at Room Temperature*				
	100°C	200°C	300°C	600°C	
RR.58	0·96	0·45	0·06	0·0	300 Hours
Hiduminium 100	(0·96)	(0·45)	0·18	—	
Ti 155 AX	(0·99)	(0·90)	0·48	—	
Alloy Steel	1·0	(0·99)	(0·97)	(0·60)	
RR.58	0·94	0·38	0·03	0	1000 Hours
Hiduminium 100	(0·94)	(0·40)	0·15	—	
Ti 155 AX	(0·99)	(0·90)	0·47	—	
Alloy Steel	(0·99)	(0·90)	(0·73)	0·11	

FIGURE 18

Alloy	*Ultimate Tensile Strength* (tons/in.²)	*Fatigue Ratio*‡ $f_{Fatigue}/f_{ult}$		*Specific Notched Fatigue Stress* tons/sq. in. / lb./cu. in.
		Plain	*Notched*	
Light Alloys:				
AL - CU	33	0·33	0·24†	78
AL - ZN - MG	39	0·26	0·19	72
Titaniums:				
5% AL 2½% SN	62·5	0·60	0·43*	165
COMM. PURE	42·4	0·65	0·49*	127
Steels:				
0·4% C	39·6	0·35	0·24	34
CR - MO	60·6	0·51	0·19	41
C - MN - CR - MO	112·0	0·40	0·28*	112

FIGURE 19. Fatigue stress ratios plain and notched.

‡ Based on 50×10^6 reversals † $K_T = 1{\cdot}65$ * $K_T = 1{\cdot}60$

stresses, and the heat flowing into the aircraft interior. Where the surface coefficients of heat transfer are high for both kinetic heating on the exterior and cooling on the interior, choice of material will make an appreciable difference to the rate of heat flow. A high value of thermal conductivity of the skin material will result in a greater heat flow to the interior than a low value.

Figure 20 shows the variation of thermal conductivity with temperature for some typical materials which may be used in airframes. It may be seen that light alloys have appreciably higher conductivities than titanium alloys and steel, while epoxy impregnated glasscloth is a very effective heat insulator. It is also noticeable that the thermal conductivity of light alloys increases appreciably with temperature whereas steel and titanium are practically unaffected.

In making a rapid assessment of the relative advantages of material from the standpoint of thermal conductivity only, it must be remembered that small surface coefficients of heat transfer exercise a considerable swamping effect on the conductor owing to the reciprocal nature of the overall conductance expression in steady state flow.

4.2.2. *Thermal Diffusivity*

In the transient state of heat conduction, and when the surface coefficients of heat transfer are large, the distribution of temperature within the conducting solid depends very largely upon the thermal diffusivity of the solid—a low value of thermal diffusivity producing steeper temperature gradients than a high one. Fig. 21 shows the variation of thermal diffusivity with temperature for various materials. The coefficients of heat transfer expected in flight at a Mach number of about 2·5 are not sufficiently large to swamp the effect of thermal conductivity at the surface so an assessment of the merits of various materials on thermal diffusivity alone may be misleading. However, it may be seen from Figs. 20 and 21 that the relative order of magnitude obtains approximately for both the conductivity and diffusivity of titanium alloy, aluminium alloy, stainless steel, and epoxy/glasscloth, the exception being magnesium. Thus, for a more nearly uniform temperature distribution in the transient state (when the rate of

heating is high) the order of preference of material is light alloy, stainless steel, titanium alloy, and epoxy/glasscloth.

4.2.3. *Thermal Stress*

For a given temperature distribution in a solid the resulting thermal stresses depend upon the product of Young's Modulus and the coefficient of linear expansion. This is well known as the thermal stress coefficient, and its variation with temperature is shown in Fig. 22 for various materials. Obviously the variation of the coefficient with temperature will depend on the independent variation of E and a, and this accounts for the initial rise for steel while aluminium alloy, magnesium and titanium all fall continuously. In all cases, however, for a given temperature distribution steel will tend to produce appreciably higher thermal stresses than the other materials shown.

4.2.4. *Thermal Stress Efficiency*

As mentioned in Section 4.2.2 when the surface coefficient of heat transfer is not large enough to swamp the effect of thermal conductivity at the surface of a heated body, the temperature distribution is determined by a complicated combination of conductivity, diffusivity, and surface coefficient of heat transfer. For the purposes of this paper a simple parameter has been chosen and named the thermal stress efficiency. This is given by

$$\frac{f_{th}\, k}{\rho E a}.$$

The justification of this parameter lies in the boundary equation:

$$\frac{dT}{dx} = \frac{-h(T_A - T)}{k}$$

for a heated solid.

This applies in both the steady and transient states of conduction. In the former the temperature gradients remain constant through the solid, whereas in the latter the initial gradient is determined by the above equation.

In general, the steepest gradients occur at early times, when the surface temperature T has not increased by very much. Thus the gradient may be expressed

$$\frac{dT}{dx} = \frac{\text{constant}}{k}.$$

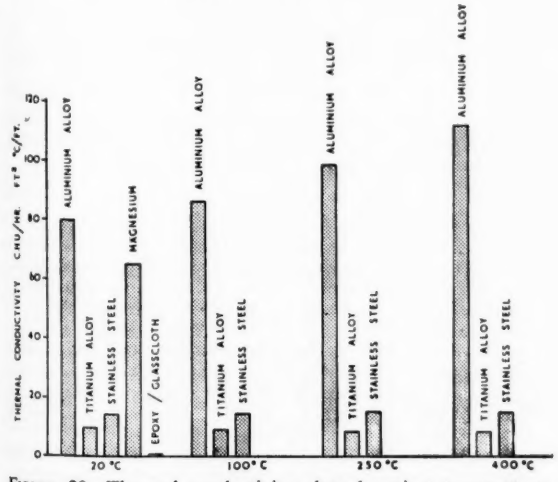

FIGURE 20. Thermal conductivity plotted against temperature.

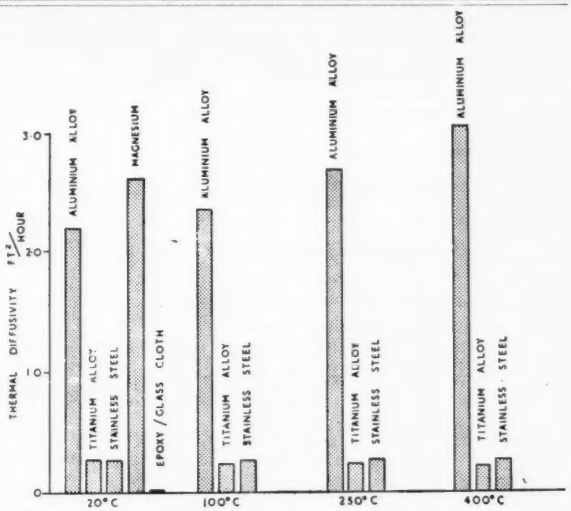

FIGURE 21. Thermal diffusivity plotted against temperature.

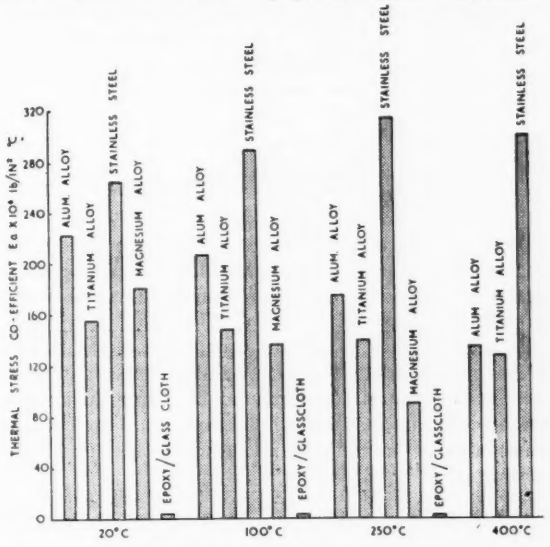

FIGURE 22. Thermal stress coefficient plotted against temperature.

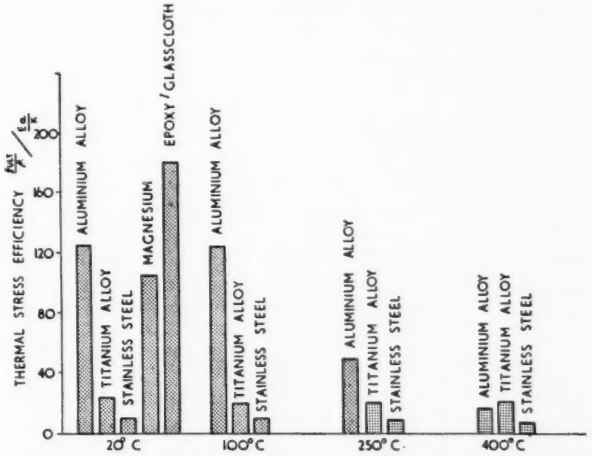

FIGURE 23. Thermal stress efficiency plotted against temperature.

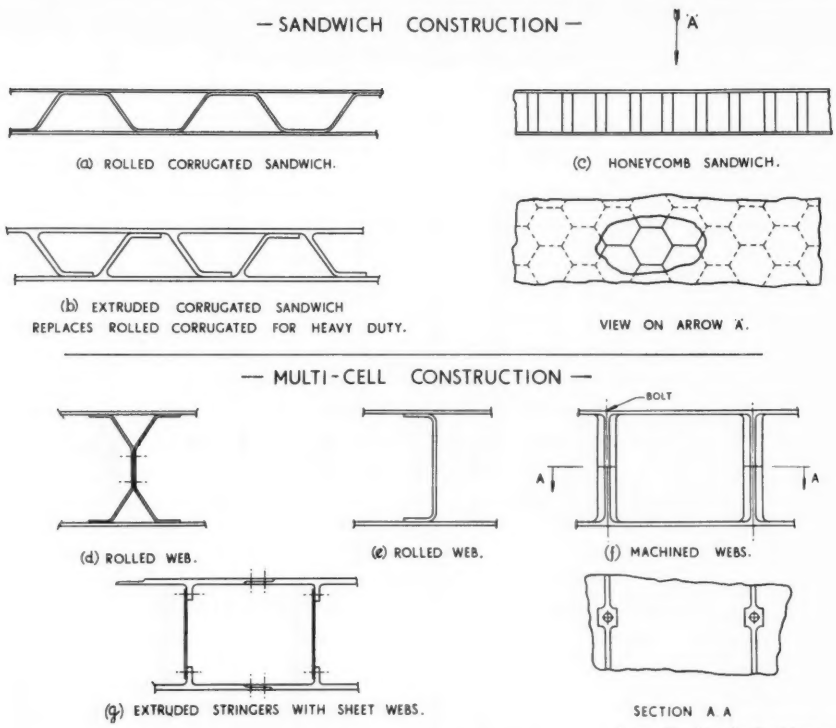

FIGURE 24. Typical structural combinations of interest.

The greater the temperature gradient the greater the thermal stress. Hence the parameter Ea/k is approximately proportional to the maximum thermal stress produced by given heating conditions.

It is quite obvious that the smaller the thermal stress is in relation to the ultimate design stress the more efficient the material is likely to be. Introducing the specific ultimate stress to account for the weight consciousness of the aircraft designer results in the parameter:—

$$\frac{f_{\text{ult}}\, k}{\rho E a}$$

high values of which tend to indicate good efficiency from the point of view of thermal stresses.

Figure 22 shows the variation of this parameter with temperature for various materials. It demonstrates the remarkable versatility of light alloys although of course at the higher temperature steel and titanium catch up. Note should also be made of the increased efficiency of titanium alloy over its rival stainless steel. This figure also indicates the useful promise of plastics. Of course the great problem here is their lack of good specific mechanical properties, their variability and, worst of all, their instability at elevated temperatures.

It should be emhasised, however, that generally material with high thermal stress efficiencies will transfer greater quantities of heat and therefore aggravate the cooling problem.

5. Typical Structural Combinations

Figure 24 illustrates some joints which are of current interest, and some of which may become of interest in the near future. The sandwich forms of construction are of particular interest in that their overall conductance is low owing to their small degree of solidity. The honeycomb and rolled corrugated core types of sandwich may be used for the skin structure of fuselages and wings if the loading is low as for, say, delta wings. They may be fabricated by brazing, or by using a temperature resisting adhesive such as "Hidux" or by "blind riveting" (although it will be difficult to produce an aerodynamically smooth surface by this method). The extruded corrugated sandwich replaces the lighter rolled core previously mentioned when the thickness of the core becomes too thick to roll, and corresponds to heavily loaded skins such as, for example, near the root section of the wing of a large delta-winged aircraft.

The forms of multi-cell construction also shown in Fig. 24 are some practical interpretations of the idealised configuration for this type of wing construction. The use of a "double" shear web as shown in (*d*) appears to be advantageous since the effective web pitch is reduced. Figs. (*f*) and (*g*) correspond to construction of the whole wing from extruded and machined components. These illustrations are typical of many structural joints and reliable information on their contact resistances is practically non-existent and it is imperative that this lack of knowledge be remedied at the earliest possible time.

ACKNOWLEDGMENT

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Guided Weapons and Aircraft—Some Differences in Design and Development

by

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(Director-General of Guided Weapons, Ministry of Supply)

The first lecture of the new Guided Flight Section (which was formed in June 1957) was also the 1050th lecture to be given before the Society, and was given by Mr. J. E. Serby, C.B., C.B.E., B.A., F.R.Ae.S., on "Guided Weapons and Aircraft —Some Differences in Design and Development" at the Royal Institution, Albemarle Street, London, W.1 on 21st November 1957. The President of the Society, Sir George Edwards, C.B.E., B.Sc., F.R.Ae.S., presided. Some 300 people attended.

Sir George Edwards: This great Society, despite its royal antiquity, had made pretty vigorous efforts during its life to recognise that aviation and things associated with it had, in fact, changed since 1866, and one of the things which it had done during the year was to form a Guided Flight Section. Discussions in the early part of the year with senior representatives of the guided weapon industry led to the suggestion that a steering Committee should be established to arrange lectures and discussions on the problems associated with weapon activities. That Committee had been pretty industrious and the Guided Flight Section of the Aeronautical Society had emerged. There had been the inevitable criticisms of Guided Flight as a title—as there would have been of anything else—and if people argued about the title it was at least a means of people knowing that there was a Guided Flight Section in existence.

The Lecture that night, which was the inaugural lecture under the sponsorship, so to speak, of this Section, was by Mr. Serby, the Director-General of Guided Weapons in the Ministry of Supply. Also, he was sure that it was not by accident that two other Main Lectures had been arranged in the same session: one by Dr. Cockburn, Controller of Guided Weapons, on Guided Weapons; the other, the Wilbur Wright Lecture to be given by Dr. Gardner, the Director of the R.A.E., on Automatic Flight; it could therefore also be regarded as part of the new Section's programme. He thought that Mr. Serby's lecture was the beginning of a pretty energetic activity aimed at furthering the Society's appreciation of guided weapons and the things that went with them. The Chairman of the Section was Dr. Gardner of the R.A.E., who, of course, was the first Director-General of Guided Weapons, the post now held by Mr. Serby who was known to a great many of them. Mr. Serby had been Director-General of the Guided Weapons Section since 1954. In 1924 he graduated from Cambridge University, spent the years from then until 1930 in Siemens Brothers and the Admiralty; from 1930 until 1938 in the Aerodynamics Department at the R.A.E.; from 1938 to 1950 in the headquarters of Ministry of Aircraft Production and, as it became the Ministry of Supply, he became Director in Charge of Military Aircraft and from 1950 to 1954 went back to the R.A.E. as Deputy Director. It was an honour that the Society should have the Director-General to read this inaugural lecture and it was a great pleasure to him to be able to welcome a personal friend. He had therefore a double delight in asking Mr. Serby to read his lecture on "Guided Weapons and Aircraft—Some Differences in Design and Development."

1. Introduction

In considering this subject we should first briefly examine how guided missiles came on to the scene. Manned flight in heavier-than-air vehicles is some 50 years old and, once the early scepticism of some critics had been overcome, very large and highly successful efforts were made to use flying machines of this kind for direct military purposes. The scope of these efforts and the measure of success that attended them are well known and have been the subject of many of the papers and much of the discussion which the Royal Aeronautical Society has enjoyed in the past 50 years or so of its 90 years of active life. It is indeed significant that the two World Wars of the past 40 years have, by reason of the extra effort they focused on military aviation, been the cause of most of the advances in aviation and thus brought about commercially and economically successful civil aviation as we have it today.

While it is certainly true that some sound and successful pioneer work towards unmanned bombers had been done as early as the 1920's and this was discussed in Gardner's paper[1] read to the Institution of Mechanical Engineers in November 1954, it is I think, equally true that it was the second of these Wars that highlighted the possibilities of unmanned air weapons which could be guided through their flight and also directed the attention of the leading nations in the world to the possibility of achieving by guided weapons, more certainly and more accurately, the military objectives which previously had been dealt with by manned aircraft. It was of course the German efforts of the 1939-45 War from which flowed this new line of thought, although the German efforts themselves did not have a long enough development time to ensure their real success. This was indeed fortunate for many of us, but we should never make the mistake of belittling the amazing guided weapon efforts made by the Germans during that War and the fact that, with only 10 years development, they produced, in quantity and for operations, weapons that were as good as were the V.1 and V.2.

The guided weapon and the manned military aircraft differ considerably in their design philosophy and therefore in the problems that they each encounter and I propose to talk about some of these differences and try to examine how far they are basic differences and how far the two kinds of weapons really share the same techniques. Fig. 1 reminds us of the superficial differences between the fighter and the guided missile, the one shown being a surface-to-air missile—the equivalent of the interceptor fighter.

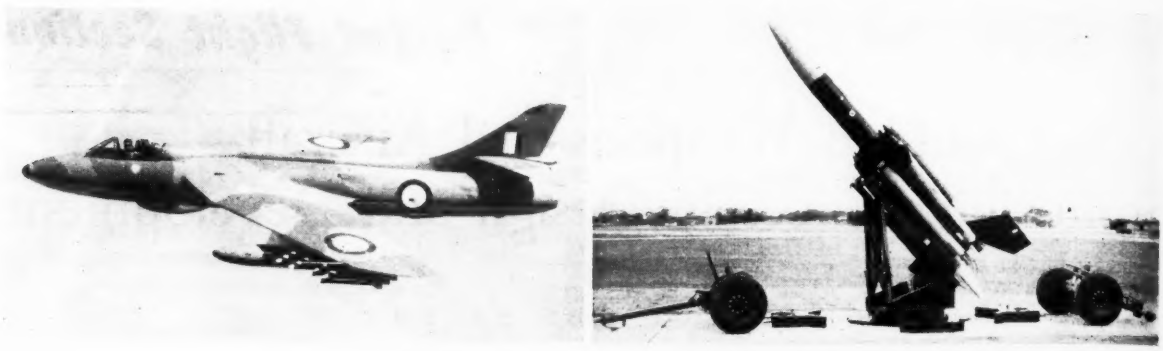

FIGURE 1. Fighter and anti-aircraft missile.

I have found it interesting to do this because I have in the past, before becoming involved in this fascinating business of guided weapons, been associated closely with aeroplane development. I have found it not only interesting but also technically profitable to do so and I submit that the guided weapon designer and the aeroplane designer have much to learn from each other. In techniques this is surely true and it is also true of regulations and procedures. The new can learn much from the old and personally I have often found it useful, when confronted with some general problem, to examine first how it was dealt with by the aircraft practitioner. A careful examination of this kind will show how much of the old practice does not apply, what can be adopted with some adjustment, and what can be transferred *in toto*. In making this comparison we must remember that the aeroplane, although it is 50 years old, is still rapidly being evolved and also that the Guided Weapon is really less than 20 years old.

2. Dependence on Radar Environment

The defensive G.W. throughout its evolutionary life has been completely dependent on a radar environment. I am here of course setting aside the offensive bombardment weapons, such as the ballistic missile, which can discard radar and rely entirely on inertial navigation. While it is true that short endurance interceptor fighters have come over the past decade to rely on radar information for their launch time, there is still some margin —admittedly getting smaller each year on account of the rise in speed of the attacking target—in the choice of the launch time. They also have a built-in ability to cruise around for some minutes; but the whole time of flight of, say, a 100-mile S.A.G.W. flying at a Mach number of $2\frac{1}{2}$ is only 3 minutes, and only 6 minutes for 200 miles. This necessitates launching at the right moment as predicted by the radar, and this moment has to be right within 20 seconds. More important even than this is the need to track the approaching target and arrange for knowledge of its position to be conveyed, preferably continuously, to the missile.

This can be done by comparing on the ground the target position with the missile position and issuing command instructions to the missile so that the two paths meet (Fig 2). Alternatively the missile can use homing information obtained by radar signals reflected from the target, the transmitting radar operating either in the missile (active guidance) or projected at the target from the ground. Another variant is beam riding where the missile rides a radar beam locked on to the target. Any of these schemes can be used to cut down, to some extent, the time margins needed by the fighter and indeed in recent years fighters have tended more and more to resort to what we may describe as automatic seeking, finding and firing at the target. The striving after shorter interception time has brought about the rocket-powered fighter in which rocket power enables the rate of climb to be enormously enhanced; the need for more

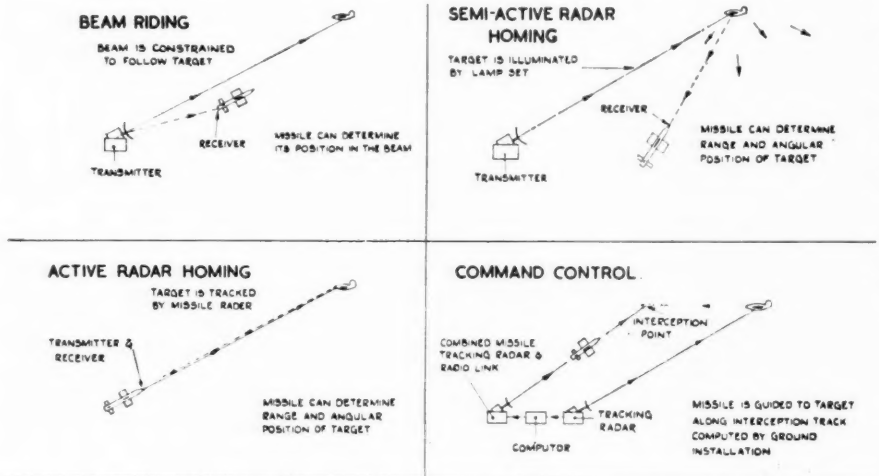
BEAM RIDING
BEAM IS CONSTRAINED TO FOLLOW TARGET
RECEIVER
MISSILE CAN DETERMINE ITS POSITION IN THE BEAM
TRANSMITTER
SEMI-ACTIVE RADAR HOMING
TARGET IS ILLUMINATED BY 'LAMP' SET
RECEIVER
MISSILE CAN DETERMINE RANGE AND ANGULAR POSITION OF TARGET
TRANSMITTER
ACTIVE RADAR HOMING
TARGET IS TRACKED BY MISSILE RADER
TRANSMITTER & RECEIVER
MISSILE CAN DETERMINE RANGE AND ANGULAR POSITION OF TARGET
COMMAND CONTROL
INTERCEPTION POINT
COMBINED MISSILE TRACKING RADAR & RADIO LINK
TRACKING RADAR
MISSILE IS GUIDED TO TARGET ALONG INTERCEPTION TRACK COMPUTED BY GROUND INSTALLATION
COMPUTOR

FIGURE 2. Missile guidance systems.

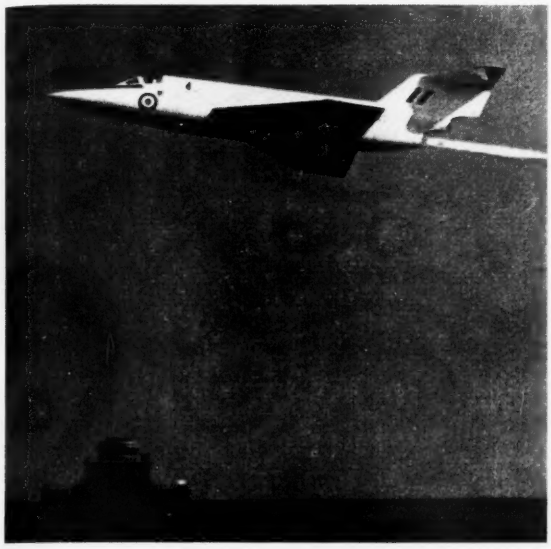

FIGURE 3. Saunders-Roe SR.53 rocket/turbine fighter.

modest thrust of longer duration to enable the aircraft to return to its base being met by the addition of an auxiliary turbo-jet engine. Fig. 3 shows this exemplified in the Saunders-Roe SR.53, which made such an interesting public debut at the S.B.A.C. show in 1957.

Thus in this all-important tactical phase the fighter has in fact been more and more nearly approaching guided weapon philosophy, and the need for a human pilot to be carried in it has rested more and more on the need to deal with take-off and landing phases of the operation.

3. Aerodynamics

Turning to the field of aerodynamics the most striking difference between the two is that the G.W. opts out of all the difficulties of take-off and landing. This of course is because it is not concerned at all with landing, and as far as take-off goes it can be accelerated very rapidly by a launching boost which will take it up to a speed at least one half of its desired cruising speed. Fig. 4 shows a typical boost assembly on an English Electric Thunderbird.

The modern aeroplane has to deal with the problem of reducing its speed from cruising to one fifth

FIGURE 4. Anti-aircraft missile showing launching boosts (Thunderbird).

or so of that speed for landing and to do this, great scientific ingenuity has been shown in providing lifting surfaces of which the maximum lift coefficient can be raised by flaps, suction, and so on. It is fascinating to note the possibility now on the aeronautical horizon of

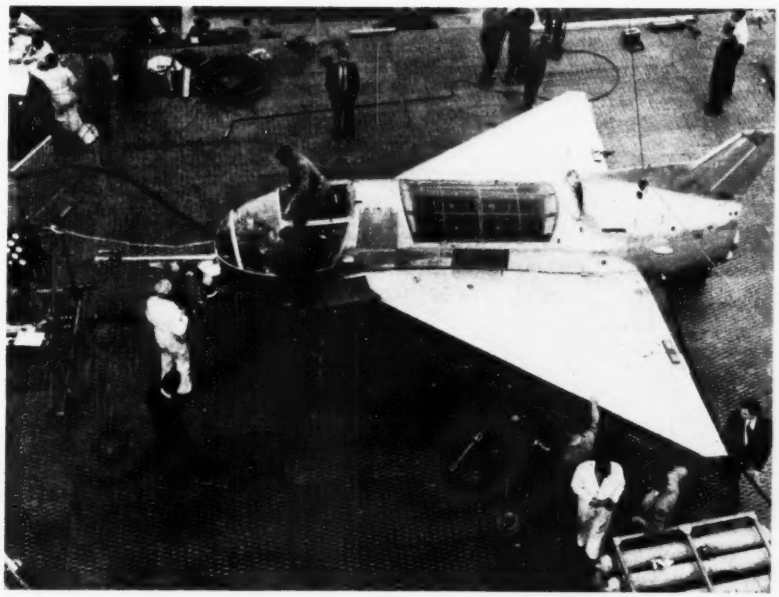

FIGURE 5. Short's vertical take-off experimental aircraft.

vertical take-off and landing by downward thrust supplied either by the normal engines or by auxiliary ones. Fig. 5 shows this principle worked out on an experimental aeroplane built by Short Bros. and Harland for a Ministry of Supply contract. The set of vertical thrusting engines is clearly visible.

Nevertheless the fact that the guided weapon has no take-off and landing speed or low speed control problems is a basic difference—one in which the G.W. is highly blessed.

The G.W. is fortunate in another major respect, that is, it can and does avoid most of the difficulties of the so-called "sound barrier," inasmuch as the rapid boost given it at launch raises its speed through the speed of sound so quickly that none of the transonic problems are at all serious. These were the problems as you all well know that were, over the past 15 years, such a hurdle—a hurdle that cost many lives.

In wing and tail disposition, shape and size, the G.W. is at first sight markedly different, but a little thought shows that much of this apparent difference arises from the fact that the missile can well operate at much higher wing loading so that the relative wing area is much smaller. For cruising at a Mach number of 2 a normal net wing loading is two and a half to three times that of a modern fighter. The wing loading of the latter must be limited to avoid an altogether excessive landing and take-off speed. This difference is brought out clearly in Fig. 6.

Most of the British, and indeed the American, guided weapons have no sweepback and this can be ascribed to the fact that, as we have previously noted, no transonic problem exists and that at a Mach number of 2 straight wings are rather more efficient than swept wings, unless the sweep is very high (*i.e.* 60° or more). Thus the highly swept delta comes into the picture, provided that the control problems can be solved and we may see more use of this configuration in the future. The choice of this plan form would seem to rest, as far as our knowledge today goes, not so much on aerodynamics as on other advantages, *e.g.* structural and weight saving. On the aeroplane side the narrow angle delta shape is already being considered for use on civil

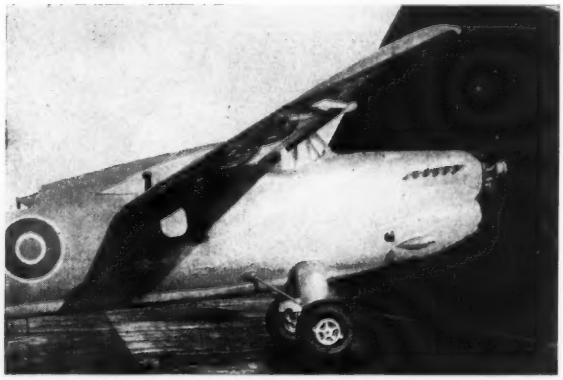

FIGURE 7. Variable incidence wing on Supermarine reconnaissance aircraft.

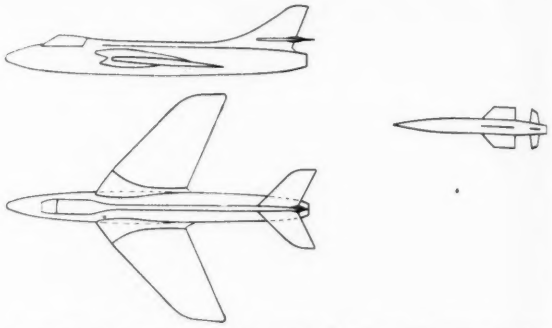

FIGURE 6. Fighter and anti-aircraft missile—differences in size and shape.

aircraft in conjunction with vertical lift power plants, *i.e.* in those aeroplanes in which it is hoped we may be able to avoid the orthodox wing lift for take-off and landing. Were it not for landing, one might be tempted to suggest avoiding this complication by providing a healthy boost for the take-off of the aeroplane but one does not imagine crew or passengers relishing fore and aft accelerations during boost of 20 to 30*g*.

A number of missiles use moving wings. Here the pros and cons are numerous. Moving wings enable the missile to achieve lift, and therefore the necessary manoeuvre acceleration, more quickly, since the inertia effect is much lower. Moreover they ensure that the body incidence is kept lower. This is advantageous in drag and means also that the radome aberration inflicted on the radar guidance beam transmitted from, or received by, the guidance equipment is reduced since the radome incidence changes are correspondingly lower. The smaller changes of body incidence which the moving wing allows are also advantageous, as far as motor intakes are concerned and this is important in the case of ram-jet engines. Moreover they lend themselves very readily to the provision of high rates of roll.

These advantages are offset by the fact that the interruption of lift at the centre section makes it necessary to increase considerably the net wing area to produce the same lift; the wing actuating mechanism is heavier and so the total weight penalty with moving wings may be considerable.

As usual the designer's choice is a compromise since he has to strike what he considers to be the best balance of pros and cons.

The idea of moving wings is not, of course, confined to guided missiles. I am sure the pioneer designers of aircraft must have toyed a lot with it and no doubt experimented with it from time to time. The only examples I can recall are the Supermarine Seagull and the reconnaissance aircraft built by the same firm. Fig. 7 shows the wing of the latter, set at high incidence.

It was fitted in this case to reduce the attitude of the fuselage and undercarriage in the final stage of landing —a somewhat different reason from the above.

Another interesting choice of wing layout that is offered to the missile designer is that between cruciform wings and monoplane. This choice has, as far as I know, never been contemplated by the aeroplane

FIGURE 8. Hannibal power plant installation.

designer; nevertheless the missile application is interesting to examine. With the monoplane layout, changes of direction are made by rolling and then pitching (hence the term "twist and steer") whereas with cruciform wings the change of direction is made by putting on simultaneously appropriate amounts of the pitch control and the yaw control. Many factors affect the choice.

The wing weight is lower (for a given wing loading) if we have only two wings instead of four. This may not be important unless the wing weight is large, *i.e.* when moving wings or large wings are fitted for high altitude operation. If fixed wings are used much larger control surfaces will be needed on the monoplane layout to provide adequate roll response, whereas cruciform wings do not require the missile to roll. This does not apply, of course, to moving wings on the monoplane because the moving wing itself provides a very good roll control.

The monoplane needs to roll and can roll rapidly, but care must be taken to avoid secondary effects of the roll—such as yaw. A further advantage is that with the monoplane layout it is easier to mount external motors and in the case of air-to-air missiles the difficulty of ground clearance under the wings of the carrying aeroplane itself is lessened.

Once again the final choice is a balance of many factors, some of which are imponderable.

An important factor in the overall aerodynamic efficiency of a guided weapon is the possibility of completely integrating the power plant with the rest of the missile. Here I am excluding, of course, the launching boosts which are shed as soon as their job is done. In most types this integration has been possible from the

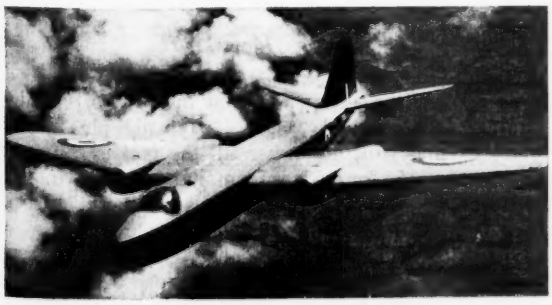

FIGURE 10. Canberra power plant installation.

FIGURE 9. Lancaster power plant installation.

start and has been realised to the full. As aircraft drags have been reduced by refinement of design, the designer has in general striven to bury his engines more and more, and from the stage when the engines were literally strung out on wires and struts between the wings of the biplane, or carried in very simple fashion on the wings, *e.g.* the Hannibal (Fig. 8), we have advanced via the streamlined wing-mounted engine nacelles of the Second War bombers (Fig. 9), to the partially buried jet engines of the Canberra (Fig. 10), and finally to a stage where they are completely buried as in the Vulcan and Victor (Fig. 11). The guided missile has in most cases gone straight to a fully buried power plant (Fig. 12). The case of the ram-jet-propelled missile is naturally different because, being an air-swallowing propulsion system, properly designed and located air intakes have to be provided. Fig. 13 shows this on the Bristol/Ferranti Bloodhound.

4. Weight and Drag

It is interesting to examine to what extent saving of drag and weight are important in guided weapon design; so far as drag is concerned the answer depends very much on the type of weapon considered. At one extreme there is the ballistic missile where, on average,

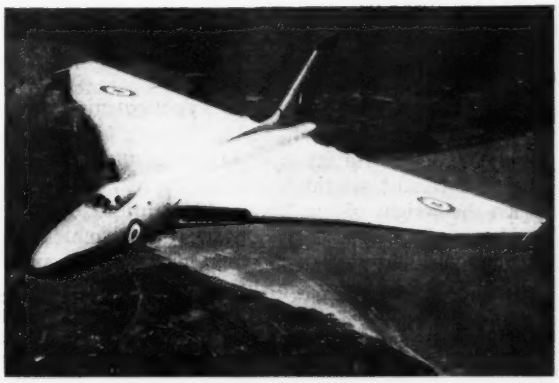

FIGURE 11. Vulcan power plant installation.

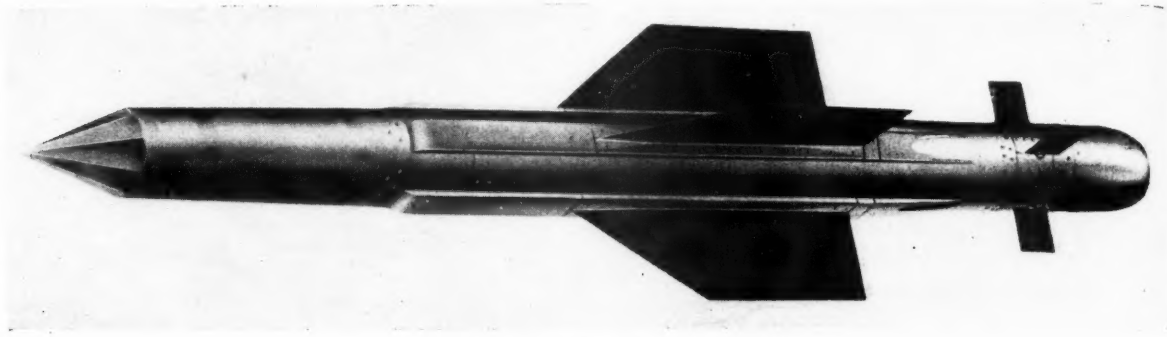

FIGURE 12. Blue Jay power plant installation.

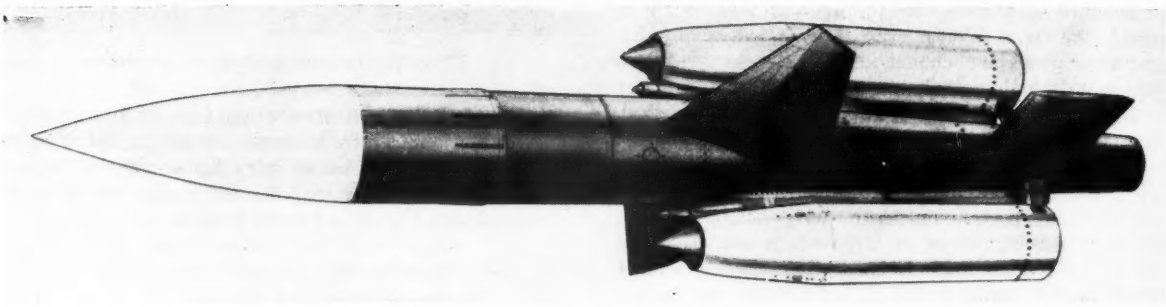

FIGURE 13. Ram-jet power plant installation on Bristol Bloodhound.

there is a considerable excess of thrust over drag and the important thing is to achieve acceleration and a high velocity by the time the thrust is cut off. The drag only operates over the time that the missile is climbing through the atmosphere, after which it has no significance. Here a 10 per cent increase in drag would reduce the range (for a long-range ballistic missile) by only one half per cent or so.

The other extreme is the longish range surface-to-air guided weapon where, after an initial climb, a considerable part of the flight is likely to be at cruising speed and in the atmosphere. In these conditions aerodynamic efficiency is demanded and a reasonable L/D ratio must be achieved, since the percentage decrease in range approximates to the percentage increase in drag. Here again we have the guided missile, when it is specialising in a particular role similar to that of the aeroplane, approaching the same design *desiderata* as the aeroplane.

As far as weight is concerned an enlightening way of looking at this is to examine the "growth factors" that apply. The growth factor is defined as the increase in the total missile weight (excluding boosts) that occurs when the weight of the "payload"—warhead, fuse and guidance—is increased by unit weight, assuming that the propulsion system, tankage, wing area, and so on, are all increased sufficiently to restore in full the original performance.

For air-to-air and the shorter range surface-to-air missiles the ratio total weight/payload, *i.e.* W/P usually decreases slowly as P increases, due to a balance between the favourable effect of size on drag and a usually unfavourable effect on structure weight. It follows that the growth factor $F = dW/dP$ should be slightly less than the local value of W/P.

In Fig. 14, F has been plotted against W/P for 12 missiles of widely varying design and it lies between 0·7 W/P and 0·9 W/P. Thus F is 2½ to 3 in the range of missiles we are considering at the moment. Compared with this we have values of F of approximately 10 to 15 in modern fighter and bomber aircraft.

In the case of the ballistic missile savings in structure weight, weight of propulsive plant and tankage are even more important. This follows simply from the fact that in this kind of missile the objective is to give it the maximum kinetic energy (and hence the longest ballistic range), so that reduction of the weights just listed is all-important, since those weights determine directly the final acceleration which will be imparted to the end stage. The basic velocity/weight relationship is given by

$$v \propto I \log_e \frac{W_0}{W_1}$$

where W_0 is the all-up weight at the start of the flight and W_1 the residual weight ("payload" plus motors, tankage, and structure) when all the fuel is consumed.

In Fig. 15, for which I am indebted to Mr. King Hele of the R.A.E., curve 1 shows "all burnt" velocity against ξ the ratio of weight of usable propellant to the total starting weight less the payload for a missile with one stage of propulsion, the payload being assumed to be 1/25 of the initial weight. On the right is an approximate scale of range—proportional roughly to

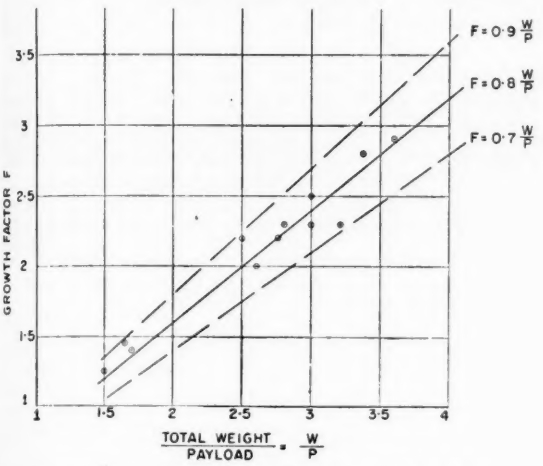

FIGURE 14. Weight growth factors for guided missiles.

the square of the all-burnt speed. Confining attention to the part of the range of ξ 0·85 to 1·0 and noting that the end point $\xi = 1{\cdot}0$ is really impractical, since it assumes zero tank weight and zero motor weight the tremendous premium attaching to reduction in those weights can be seen immediately. At the point on the curve corresponding to $\xi = 0{\cdot}90$ we see that a one per cent improvement in ξ gives a 5 per cent increase in all-burnt speed and a 10 per cent increase in range. From this it becomes quite clear that the designer will always be striving after greater efficiency in the design of his tanks, motors and motor supporting structures.

Compared with this the position of the long-range aircraft is indicated by the classic range formula

$$R \propto L/D \times \frac{1}{c} \log_e \frac{W_0}{W_1}$$

Whereas the ballistic missile can expect to achieve a W_0/W_1 of 20 or so, the long-range aeroplane is doing well to achieve a value of 2. The fundamental difference between the two methods of delivering a load at long range is seen by comparing these two equations. In the missile case the range is proportional to the square of the logarithmic weight function whereas it is directly proportional to it in the case of the aeroplane. This arises from the fact that the aeroplane expends its fuel energy in steadily overcoming its own drag, whereas the ballistic missile is hardly concerned with drag and uses its fuel energy in imparting kinetic energy to its "payload."

Staging, by which is meant discarding at one or more points in flight such of the tankage as has been emptied and some of the power plant, can be used in both to advantage. The principle is well known in rocketry. The other curves marked 2, 3, and so on, in Fig. 15 relate to various amounts of staging and the family shows how the choice of the number of stages is dependent on the parameter ξ (the fuel carrying efficiency factor). Staging has also been used in aircraft as far as the discarding of tanks is concerned. It could conceivably be carried further in aircraft and

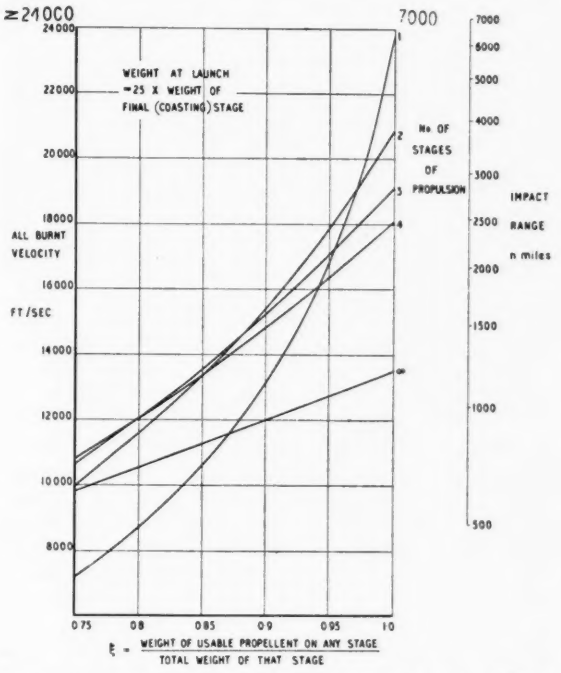
≥24000
7000
WEIGHT AT LAUNCH = 25 X WEIGHT OF FINAL (COASTING) STAGE
No OF STAGES OF PROPULSION
ALL BURNT VELOCITY FT/SEC
IMPACT RANGE n miles
ξ = WEIGHT OF USABLE PROPELLENT ON ANY STAGE / TOTAL WEIGHT OF THAT STAGE

FIGURE 15. Consumable-weight range characteristics for ballistic missiles.

calculation shows that it is one way of reducing considerably the take-off weight of the long range aeroplane.

5. The Development Cycle

So far I have been discussing differences in technique; let us now look at the whole design cycle (Fig. 16) and see how the two cousins differ and why. The two sides of the table look very similar but a closer examination reveals some fundamental and important differences. Note first the extensive use, in the guided missile cycle, of simulators, both in the assessment phase and in subsequent development and trials. Next there is the extent to which the guidance equipment is given an all-important part in the early layout stage. For example, if homing guidance is to be used then the homing receiver must be in the nose, whereas if command guidance is used then the nose can be used to accommodate other equipment. The A.I. set in a fighter has a similar influence but this does not apply to the bomber. In the same way, the warhead bay position in the guided weapon has to be given careful consideration to ensure that the destructive effect of the warhead is not lowered by structural interferences. In the case of the bomber where the warhead explodes at a point completely remote from the aircraft, provided that the bomb load is reasonably near the c.g. and an adequate bomb aperture is provided, all is well.

Both aeroplane and G.W. have made use in the early design stages of scaled flying models. Custom in this respect has changed markedly from time to time and we cannot point to consistency one way or

the other in either type. The case for flying models for the missile may no longer be a strong one. To design and build them takes time and money and these might, with better advantage, be put into wind tunnel tests. The situation for the aeroplane was somewhat different when wind tunnel work was not so successful in aiding the design of the controls, the feel of those controls being all-important to the pilot. We should note in this connection, however, the extensive use that has been made of small-scale ground-launched boosted models to test particular aspects of guided weapons. These are really supplementary to wind tunnel tests.

In the matter of wind tunnel testing there is much that is in common in the orthodox field of stability and control testing. The high incidence region has, however, to be more fully investigated for guided missiles and particular attention paid to cross-coupling effects as has been noted earlier. The guided missile has its own particular problems in respect of boost carriage, boost efflux and clean jettisoning of the boosts. Much more significant differences are met of course with long-range ballistic missiles, notably the problem of providing a turning control when the missile has reached a height where the normal aerodynamic forces employing the properties of the atmosphere are unavailable. The re-entry into the atmosphere brings us sharply into the hypersonic aerodynamic region and avoidance of catastrophic burn-out demands considerable research to determine the best shapes and the heat transfer conditions that apply in this region.

Both use flying test beds to some extent—the aeroplane designer relies on extensive test bed work for the development of his engine to give him a reliable engine and similar test bed flying is necessary to develop the radar equipment and suchlike. The missile designer can and does use the aeroplane to a considerable extent to carry, on flight trials, his guidance and homing systems before they are even put into a missile. Similarly, cheap simple test vehicle rounds are used to prove boost and sustainer motors.

Moving on to the prototype stage, the aeroplane must as soon as it first takes the air, be complete in respect of controls, propulsion; in fact it must be as *complete* and sound a flying machine as can be devised. I do not mean complete in respect of radar and navigation aids but as a flying machine it must be complete. The missile on the other hand can deal with its many problems one by one and only when each is satisfactory need the whole system be buttoned together. The control and guidance system can, for instance, be omitted in initial rounds designed to prove the propulsion and drag, then the controls can be fitted and their effect measured by giving to them a series of command instructions. The guidance system can be developed on rounds that have no controls working and when all is satisfactory the loop from guidance to control and back can be closed. Ignoring the fact that some of these tests on the separate parts of the missile can be made on test vehicles which need not all be of precisely the same form as the final prototype, and grouping all these test vehicles together with the final prototypes, we find that some 200 missiles have to be

DEVELOPMENT CYCLE

Aircraft	*Missile*
Assessment; choice of layout, W/S, power plant, etc.; type of controls, flaps, etc.	Assessment supported by simulator studies; choice of guidance system in relation to warhead and fuse; choice of layout, power plant, etc. in light of above.
Wind tunnel model work	Wind tunnel model work together with ground launched models (rocket propelled).
Scaled flying models	
Flying test beds to prove power plants, etc.	Propulsion rounds provided simply to develop boosts and sustainer.
	Test vehicles to develop power plants, explore aerodynamics, boost separation, etc.
Prototypes 2-6	R. and D. rounds 100-200.
A. & A.E.E. testing	Acceptance rounds 50-200, amplified by simulator work.
Production	Production.

FIGURE 16. The development cycle, aircraft and guided missile.

flown in the course of development, whereas between two and six prototypes serve for the aeroplane development. This follows, of course, from the simple fact that the aeroplane prototype always (or nearly always) lives to fly another day, whereas the missile prototype once fired is usually lost at the end of the flight. This is very expensive and puts a high premium on ensuring not only that every part of the missile works, but also that the required data is properly transmitted back to the ground. If a fault develops in flight in a prototype aeroplane the fact that there is in charge of it an experienced human pilot means usually that that fault does not result in catastrophe. If the same happens in a missile one is very lucky if the required data are obtained.

This inevitable difference in the number of specimens used in the development cycle carries through to the acceptance phase in which an independent test station flies (or fires) the equipment to determine whether it comes up to specification and is fit to hand over to the user.

Two important points have been brought out in this brief sketch of the differences in prototype development. firstly the vital need in the case of the missile to transmit back to the ground accurate measurements of the behaviour of all parts of the system and, secondly the high premium that attaches to reliability.

6. Telemetry

The aeroplane need not use, and only rarely has used, telemetry but missile development simply could not proceed without efficient telemetry. A certain amount of recording on equipment carried in the missile has been done in the past but shortage of space,

which prevents sufficient recording gear being carried to deal with all the information required and the high risk of loss of the records at the end of the flight, makes the extensive use of telemetry mandatory. As a result a vast amount of work has gone into the development of this highly sophisticated art. Firstly a wide range of transducers had to be developed to convert electrical signals, mechanical movements, pressures, and so on, to convenient forms of electrical signal which the switching and radio link of the telemetry could handle and lastly, the receiving and recording gear on the ground.

The total time of flight available for the collection of data may be only 10 seconds, and during that time information about the propulsion, aerodynamics and guidance and control responses to a variety of naturally evolved, or commanded, manoeuvres may all have to be signalled back to the ground. The parameters that have to be examined vary from transient phenomena such as wing flutter, which requires continuous channel recording, through combustion chamber pressures which require less frequent sampling, to lateral and longitudinal "g" measurements, angular yaw, pitch or

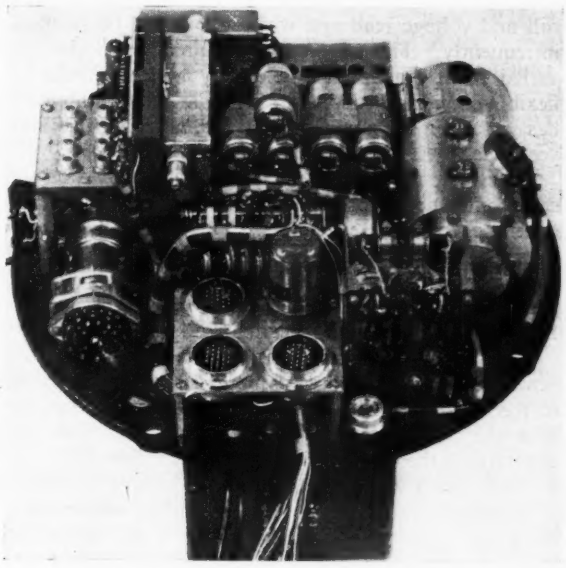

FIGURE 17. Typical airborne telemetry assemblies.

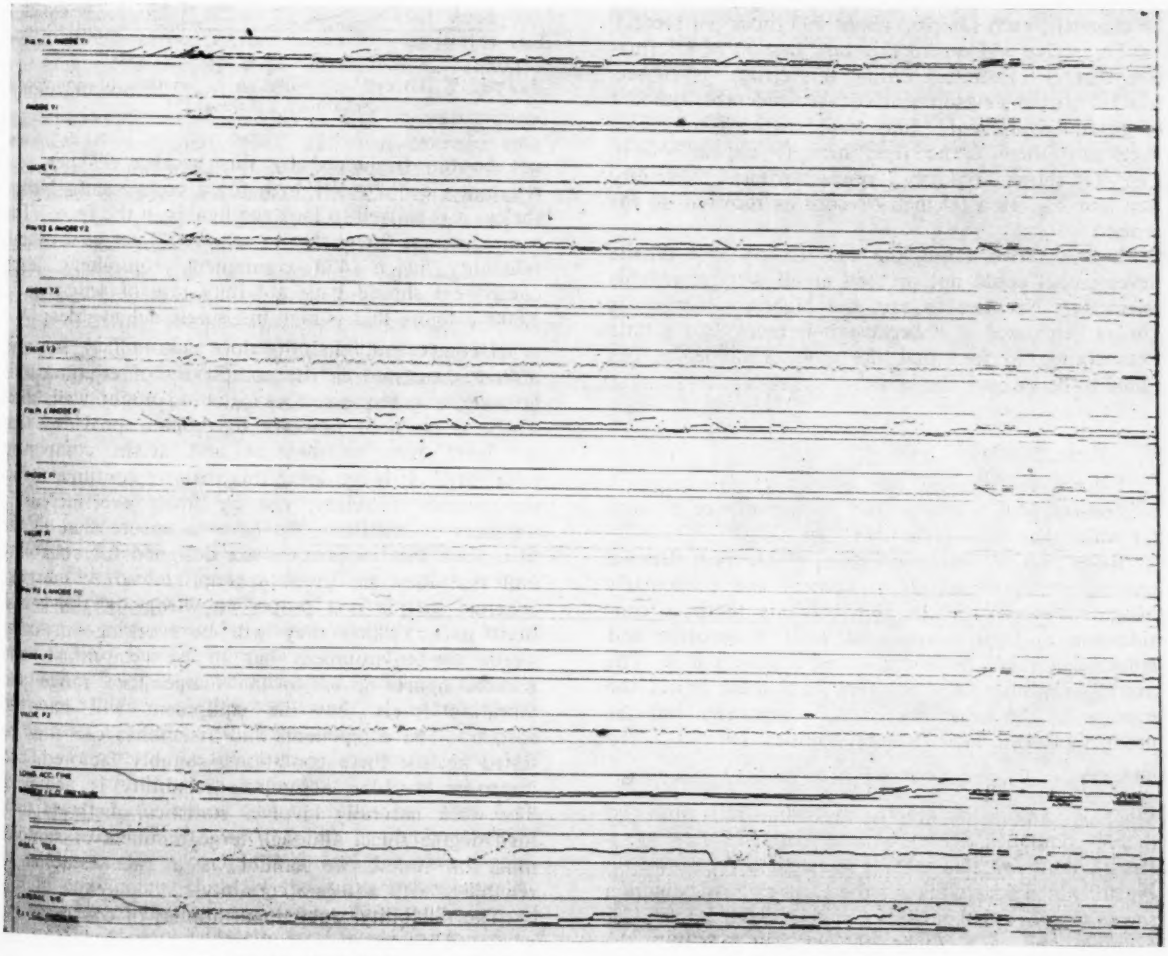

FIGURE 18. Typical telemetry record as delivered by the ground receiving equipment.

roll and voltage readings, which need only be sampled infrequently. The transducers required to do this are varied in design and the telemetry system should be flexible enough to cope with them all. No requirement has yet arisen for strain-gauge types, although this may yet come.

There are several current systems, each based on the same fundamental principles, but which differ in detail depending on their exact role. Fundamentally, a telemetry system consists of two parts, an airborne sending equipment radiating by means of aerials on the missile, which must be chosen and sited to give a good Polar Diagram, and a ground receiving equipment.

The sender consists of an oscillator varied in its power rating from 2-20 watts up to 100 watts according to the missile range, suitably modulated in accordance with the parameter being measured. To increase the capacity of the equipment a high-speed switch is used in conjunction with the modulator to sample a number of parameters in turn, one position of the switch being normally used for synchronisation. If additional capacity is required, one or more channels may be sub-commutated, although naturally the sampling rate is correspondingly reduced. One standard system provides 24 channels, each sampled about 100 times per second.

To receive and record this vast amount of information that is transmitted during this critical 10-20 sec. has led to the development of a considerable amount of ground equipment. This would make a subject in itself and there is no time here to expand on it. Fig. 17 shows a fairly typical airborne telemetry unit and Fig. 18 a telemetry record as received on the ground.

It is not overstating the case to say that missile development could not proceed at all without reliable telemetry. Needless to say, the highest reliability is always demanded of it because it is more than a little exasperating to find that the monitoring device has failed to bring back the news!

7. Reliability

I have touched on the subject of reliability in connection with telemetry but its importance extends far wider than that single field.

Reliability is coming to be one of the most debated characteristics of military equipment and particularly of guided weapons. In spite of this there is considerable misunderstanding of what it involves and indeed, ignorance of how involved a subject it is. The overall reliability of a complex equipment is not the *average* of the reliability of its components but the product of their individual reliabilities, *i.e.*

$$P \text{ overall} = P_1 \times P_2 \times P_3 \ldots P_N.$$

Where P_1 and so on are the individual reliabilities of the N components. The simple but shattering arithmetic result of this simple statement is shown in Fig. 19 which I have taken from Lusser[2]. This diagram shows that if the equipment has 100 components, for example, and each reaches 99 per cent reliability the overall reliability will be about 35 per cent. We should

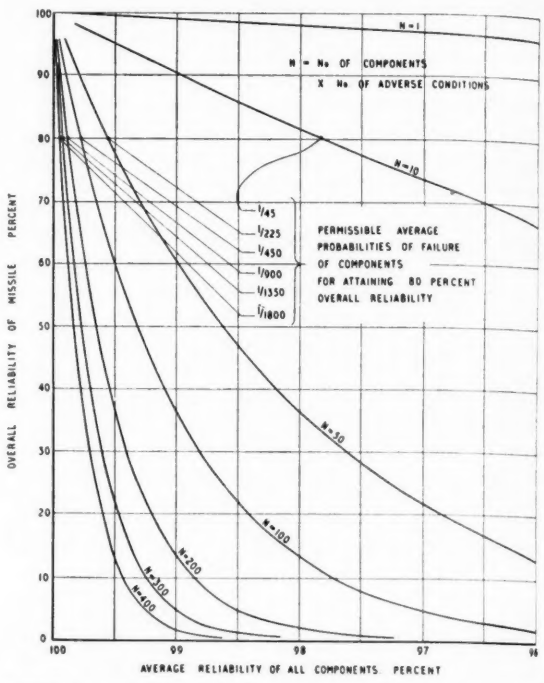

FIGURE 19. Overall reliability as a function of component reliability. (LUSSER[2]).

not be too frightened by this because 99 per cent reliability is not really high for a component. Nevertheless it is as well to look the figures in the face. The same diagram shows that to achieve 80 per cent overall reliability in a 400 component equipment, each component should have a failure rate of only one in 1,800, a figure that is high but surely achievable.

If component reliability does not, in fact, improve at the same rate as the complexity of equipment is growing, a growing serious situation might well arise. There is no need however to despair, provided that we learn how to measure and attain component reliability. It is by doing this that we continue to lift the overall reliability, not by firing ever-increasing numbers of missiles. We have to ensure that in the first place the components are designed for reliability and that they are given appropriate safety margins. Inherent in this is a proper knowledge of the conditions under which they will be working—in other words the environment has to be established—and reliable figures given to the temperature range and vibration levels that the equipment will have to sustain. The components and assemblies can then be tested against these conditions, suitably factored, and improved until an acceptable reliability is achieved. The work naturally involves statistical methods to a high degree since, although large numbers of samples must be tested, we cannot as a rule establish a reliability with absolute certainty.

The reliability requirement applies of course to the whole G.W. system including the ground radars, the control posts and the launchers, although the missile

will always be the most critical part of the system since its environment is worse and its components have of necessity to be reduced so much in weight and size.

Flight reliability of the missile is not the whole story however; the hazards of transport, storage and handling have to be considered as well and in some service environments these can present more difficult conditions than those met in flight, or at any rate, different conditions.

In production, quality control methods are essential and special care needs to be taken if sources of production are changed, otherwise reliability will drop at every such change.

Comparing the aeroplane with the guided missile the differences seem to be these. As far as the likelihood of the aeroplane completing its flight are concerned the conditions against which the aeroplane is designed are now so well known that the chances of the flight ending in disaster, say by wing failure, are very small indeed. The aeroplane, even the civil one, is highly complex but it can survive the failure of quite a few of its complex components. I would hazard a guess that at the end of most long intercontinental civil flights one half to one per cent of the complex equipment is not working. This does not prevent a safe arrival. One reason for this is that the aeroplane is equipped with alternative or standby equipment which can be brought into use if the primary equipment fails. This in turn depends on the presence of a human pilot who can exercise this discretion. The guided missile, designed down to a minimum of size and weight, does not have this ability. The picture changes as automatic devices take over more and more duties on the aeroplane and this is especially true of the military aeroplane where its target recognition, target seeking, bomb aiming, even its stability, are having more and more to rely on electronics. In other words the military aeroplane is coming more in line with the G.W., where, in general, failure of one component will prevent a successful mission.

8. Missile Recovery Techniques

We have noted already the large number of prototype equipments that are usually required. The expense involved in firing such a large number is high and any successful method of recovering the test vehicle or prototype after flight would clearly be of great value. Besides permitting the use of equipment for further firings, recovery is often useful in providing positive evidence of the behaviour, or misbehaviour, in flight of critical parts of the airframe or the equipment. Telemetry is of tremendous value but its evidence is often of a secondhand nature when an unexpected fault arises and the cause of that fault may, if only telemetry records are available, have to be arrived at by a complicated, and not always completely convincing, chain of deductive reasoning. As an example of this let me quote a case that occurred during some ram-jet development trials in Australia. A failure previously ascribed, from consideration of the telemetry records, as being due to poor air/fuel ratio control, was found, upon recovery of the actual test vehicle, to have been caused by flare failure resulting from rough burning.

For these reasons considerable experimental work has been done on recovery methods. They differ in degree, according to the effect desired, the space available in the missile and the surface on which the vehicle is intended to land. This may be the sea, as at Cardigan Bay, or land as at the Weapons Research Establishment at Woomera, South Australia. In both cases the initial problem is to slow the vehicle down before it makes impact and one way of doing this, probably the simplest, is to arrange for the head to be broken off by an explosive charge when the missile has completed its useful trajectory. The increased drag reduces the impact velocity to about 250 f.p.s. An examination of the vehicle is quite a practical proposition although components can seldom be used again. More sophisticated systems aiming at complete recovery have been developed both by the Bristol Aeroplane Company and the English Electric Company for their missiles. Using multi-stage drag-producing devices, either air brakes or parachutes, the vehicle is slowed down to impact at about 60 to 70 ft./sec.

Figure 20 shows a Bristol test vehicle after landing; notice that it lands on a spike which assists in the final deceleration. Bending of a weak neck in the spike helps to take out any drift in landing. An English Electric test vehicle using their system of recovery has been flown a second time—convincing proof of the

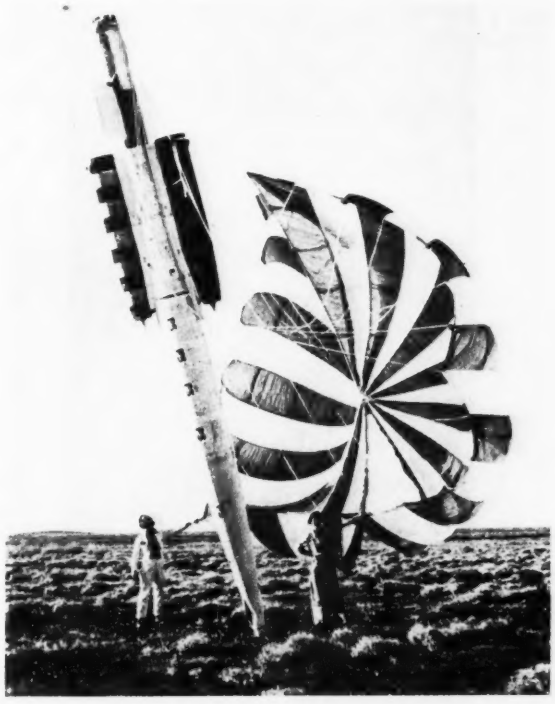

FIGURE 20. Bristol recoverable test vehicle.

economy of the system. Recovery on a sea range is a rather different task and having in mind their own particular problems in Cardigan Bay the Royal Aircraft Establishment has successfully developed a bouyancy system which permits recovery on a sea range, although clearly the corrosion problems are severe and it would probably not be profitable to redesign the whole missile to make it sufficiently watertight to prevent damage to the internal equipment; nevertheless inspection after recovery is still of great value. Even more ambitious and potentially profitable is a system on which the Weapons Research Establishment at Woomera is working. This is aimed at recovering the missile in flight; if this is successful, and it has reached this stage for small vehicles, it offers wide possibilities of re-use.

FIGURE 21. Interception from wing tip camera.

Clearly this is one direction in which the manned aeroplane has a great lead over its cousin and although guided weapons are making efforts to close the gap they are always bound to be at a disadvantage, except possibly when serious trouble occurs in the development stage when the major portion of the guided weapon may be recovered, whereas the aircraft may be a total wreck.

9. Trials Ranges

In trials range techniques there is a wide difference between the guided weapon and the aircraft. For the latter, instruments carried within it suffice to determine nearly all the performance characteristics. Only occasionally is it necessary to resort to ground-based observations, such as camera theodolite, or ground radar to check the "position error" of the Pitot-static head. The aeroplane's performance can therefore be measured in almost any part of the sky by self-contained methods.

In contrast to this the guided missile can carry few such instruments and these must transmit their information to the ground, since in general only a small fraction could be stored in the missile itself. Our concern is not to measure "time to height" or speed but, to establish that the guidance system and all the associated equipment is functioning satisfactorily—and finally that when it reaches its target either the hit or the distance of miss is recorded. Thus, not only is it necessary to launch the guided weapon and observe from the ground its behaviour, but it is also necessary to fly an unmanned target aircraft and this brings in its own control and instrumentation problems. The subject of targets is a big and interesting one and will be discussed in a lecture later in the season.

Figure 21 is an interesting series of pictures taken by the wing tip camera mounted on a Firefly target. They show the wing and fuselage of the Firefly itself and in the first frame the attacking weapon—a Fairey Fireflash can just be seen near the tail wheel, while the last frame shows that the tail wheel has been knocked off by the weapon.

The firing range must be equipped with optical and electronic tracking devices to establish accurately the flight path of the missile; telemetry receivers must record missile component behaviour; a complex communications and timing system is required to synchronise the operations and observations of both missile and target aircraft. Much of the radar equipment is conveniently located near the launching point but optical and some other electronic monitoring devices have to be spaced out along the flank of the range.

Figure 22 shows a typical layout in the launching area at Aberporth and Fig. 23 a camera observation post at the side of the range.

FIGURE 22. Ground installations at Aberporth.

Ideally the range itself must be greater in length than the range of the weapon under test and the safe area must extend to each side to allow a certain latitude in azimuth. Where this is not possible, the flight time of the missile must be limited. With an aeroplane the trials range for its weapon is determined only by the scatter pattern of the ballistic path bombs under test, or by the few miles needed to cope with the air range of the shells from its guns. It is the selection of such an area capable of being developed to the required degree, quite as much as the expense in instrumenting it, which is one of our biggest problems. I am sure you will be hearing a lot more about ranges in later lectures.

10. Conclusion

In this lecture I have tried to bring out some of the differences between the guided weapon and the aeroplane and to examine whether they are fundamental or merely superficial. I wish here to thank my staff and my colleagues for the assistance they have given me in preparing this paper. I certainly do not claim that my list of differences is exhaustive and such as I have spoken about I have not dealt with exhaustively. I have not, for instance, attempted to deal with guidance in itself nor of the way in which it has to be integrated completely with the control system. The integration of these two together with that other vital organ, the fuse, is indeed the very essence of guided missile design, and in it lies the biggest difference between it and the aeroplane. By integration I mean here what may be called circuit integration, that is the planning and linking together of the many functional equipments which go to make up the missile system. Integration in the case of the guided missile has, however, another important and more literal meaning and that is the physical integration necessary to house so many items in a comparatively small space. The word system as applied to military aeroplane design has come to mean much more over the past 10 years, but in spite of that change its meaning in relation to guided weapons and the full significance of the word integration in them is still much greater than in the case of the aeroplane. Guidance and controls are vast subjects in themselves and warrant treatment by experts, and this is planned to take place later in this season's programme.

I have not spoken in any detail of propulsion systems and fuels, the important new lines of research and development in structures, the use of simulators to augment in an economical way the results obtained from test firings, of inertial navigation systems and components, or miniaturisation of components, nor of many other important fields. These and some topics I have mentioned will, I trust, be the subject of further lectures.

If I may now try to sum up I would suggest the following conclusions:

1. The two types, from having been widely apart in their origins and conception are now, in fact, rapidly getting nearer in their design philosophies and in their techniques.

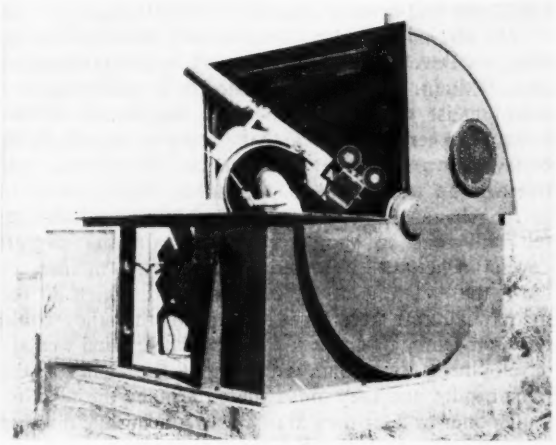

FIGURE 23. Observation post with high-speed camera.

2. In spite of this the fact that one carries a human monitor still results in considerable differences. Whether, and when, the penalties of so doing will result in his disappearing from most of the military aeroplane roles is a matter outside the scope of this lecture.
3. In much of their make-up—aerodynamics and propulsion—the basic scientific thought and skills are really very similar.
4. The G.W. design has much to learn from the aeroplane design and vice versa. If in the past 10 years they seem to have grown up in different schools this is unfortunate and the time is ripe to see a greater merging and a greater sharing of knowledge and experience.

The Royal Aeronautical Society, if it lives up to its long and fine traditions, has a wonderful opportunity of bringing this about.

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DISCUSSION

Sir George Edwards: He thanked Mr. Serby for a stimulating and interesting comparison between these two devices. A good many of them had felt over the years the wisdom of the fourth conclusion that much had to be learnt from one to the other, and the inference that the learning had not been fast enough had, he believed, been shared by a good many.

H. H. Gardner (Director and Chief Engineer, Military Aircraft, Vickers-Armstrongs (Aircraft) Ltd., *Fellow*): They owed a great debt to Mr. Serby for sending off the work of the Section in such a magnificent fashion. They had started the first of a series of Guided Flight Lectures, and he must confess that as a Member of the Steering Committee he was in some trepidation as to what would happen there that night. He thought that they could all agree that they had had a magnificent start which he hoped would continue in the series of Guided Flight Lectures. Mr. Serby, in pointing out the differences between Modern Aircraft and Guided Missiles, had shown how much closer they were together than many of them in the early days thought. In fact Mr. Serby's remarks had made him realise that many of the things they used to regard as differences were not differences at all. They were differences in the psychological approach on the part of staff, and he believed that in his last words in conclusion, when he said they were getting together far more rapidly, Mr. Serby had given a sound piece of advice.

He was impressed with the twenty years of Guided Weapon Development as compared with fifty years of aircraft flight. This fact was enough to make many of them realise that they came into the picture in this country rather later on in that twenty years which, he believed, was of great significance. There was one question he would like to put to Mr. Serby, which in his conclusion he said he deliberately omitted, but he felt still that he should go ahead. In the aircraft development side they were faced by the number of crew; that was one of the problems with which all the modern aircraft were faced—as to whether they could have two, three or go back to one. The guided weapon development was going on without the help of the human pilot and they must, therefore, face the position that sooner or later they must start reducing the number of crew in their plans for future fighter aircraft. That, he knew, was a contentious point, and he hoped he could put this to Mr. Serby in spite of the fact that it was not an easy one to deal with. They were well acquainted with the point which Mr. Serby brought out so clearly in his lecture and were delighted to hear his remarks about the problems which were not faced by the Guided Weapons engineers in landing and take-off, and his remarks on the lack of difficulty which faced the Guided Weapon designer in pushing these projectiles through the transonic range. Although in the early days this was feared to some extent by missile aerodynamicists, it was not nearly such a problem as expected, and he thought they had all learnt that, in general, the aerodynamics of that stage of the guided weapon had been far more simple than was originally anticipated.

Mr. Serby mentioned reliability. This was a major point in Mr. Serby's paper and it was a major point in all discussions of guided weapons, and there was a great deal to be said on the reliability not only in guided weapons but in the equipment in aircraft. It was clear that none of this equipment was yet reliable enough, but they hoped future lectures of the Guided Flight Section would outline this problem for the overall weapon system.

In the formation of this Section there had been some difficulties, of which he should like to tell them at length, such as how they reached the name "Guided Flight," but this would take too long even to be begun. However, he thought that he should mention that at the R.A.E. the chief contender for the name was "Rocket Section," and it was only by a very narrow margin that this name was not forwarded to the Council as the recommended name of the present Guided Flight Section. It was intended that interest should centre round the overall weapon system, and he felt that here there was a very wide scope.

Mr. Serby had done them a great honour in giving the paper and showing the actual scope and the amount of work which could be presented in such lectures; they were, he feared, all trying to look in this modern screen of the new and very latest ground radar—not yet in production—and when one thought of those little spots on the screen and pondered how many were aircraft and how many guided weapons, one wondered. They knew the picture was there, they knew many of its problems. There was much to discuss but he believed that with this inaugural lecture they had now launched a section of the

Society suitable for an era which he gathered was now being called "Neo-satellite."

S. Scott Hall (Scientific Adviser, Air Ministry, *Fellow*): If aircraft designers and guided missile designers were going to understand one another, they must have a common terminoiogy. He had never heard of a cruciform aeroplane, and control by twist and steer must be equally strange to an aircraft designer. Might he also be forgiven, having heard this Section, named the Guided Flight Section, for wondering what the rest of the Society was now to be called. He could only imagine it would be known from now on as the "Mis-Guided Section."

M. B. Morgan (Deputy Director, Royal Aircraft Establishment, *Fellow*): Might he pose a question on reliability. It seemed to him that the people sitting in this lecture theatre were a pretty reliable lot. If they were constructed on the principles described by Mr. Serby for his missiles—large numbers of component parts largely in series—there would have been stretcher cases being carried out of the room during the lecture at a furious rate; because they had thousands and thousands of small components inside them, all individually quite unreliable.

Yet here they all were, looking quite cheerful. Fortunately the human block diagrams involved very large scale duplications and redundancies; this safeguarded them against one little failure bringing the whole body to a grinding halt.

Similarly in aircraft practice, it was customary—when dealing with a vital piece of mechanism—to duplicate and possibly arrange for automatic switching to an alternative mechanism in the event of failure. Multiplication of the power plants was an obvious example; powered flying controls provided another example, in this case often with automatic switching from the failed component.

Mr. Serby, in describing the philosophy of missile design, suggested that considerations of space and weight ruled out duplication of components. He could not help wondering whether this line was sustainable in the long run; the guided weapon designer might—in the event—be forced to a certain measure of duplication of particularly tender components.

For a variety of reasons there had been a tendency to throw man out of the thing that flew through the air. The fighter was replaced by the anti-aircraft missile. The bomber by the ballistic missile or the flying bomb; and so on. Having taken the man out of the vehicle, did they make enough use of him on the ground? When considering certain command control systems, for example, he had always been impressed by the great simplification—and hence greater reliability—achieved by making full use of a man's learning capacity, skills, and reasoning powers rather than relying on complete automaticity. He would welcome Mr. Serby's views on this, and would like to add his thanks for a most stimulating and interesting lecture.

Mr. Serby: Concerning Mr. Morgan's first point on reliability—that there was useful redundancy built in to the human framework and there seemed no reason why they should not build similar redundancy into guided weapons. So far as he knew there had never been any deliberate attempt to do this, in fact all their endeavours had been to develop to a satisfactory state one set of components and to avoid putting in insurance measures in case part of the system failed. He felt that if they once started on a policy of building in insurances they might not know where to stop.

Mr. Morgan's second question was—why not make some use of the human beings some of whom were now being thrown out of the aeroplane by giving those men a job to do on the ground in the way of intelligent monitoring. Might he first say that he did not advocate throwing all the men away, he merely said that this could be done if one so wished. He thought the answer to this suggestion was that the man on the ground could not cope in speed of reaction if he were expected to perform a function within a fully automatic fast-moving system such as the ground control of an anti-aircraft weapon. In some of the simpler guided weapon systems, however, it had been found very profitable indeed to harness up the human brain and the man's visual powers and his reaction thereto as well as his great skill in doing things quickly, to observe the path of a missile visually and then to let him command control it to its target. For comparatively simple vehicles at short ranges this had been found an extremely valuable combination of automatics and human ability. There was here, at least, a partial answer in the direction in which Mr. Morgan was pointing. If, on the other hand, the suggestion was that man should monitor the system in the sense of observing the correct functioning of the automatics and should arrange the switching off of an S.A.G.W. launching system if any failures showed up, then this was already provided for in such systems.

V. N. Butler (Omes Ltd., *Associate*): He came to this lecture because of the title "guided flight." Was he right in assuming that there was no future for applications other than military within the dim distant future for guided flight?

Mr. Serby: He had not himself given very much thought to this because most of his workday was taken up with dealing with the military application, but he supposed some applications other than military ones were feasible. For instance, he had heard that some people in America had proposed to deliver mail at a range of 700 miles in a ballistic missile, but whether they were serious or not he did not know. There was also a conceivable use for an orbiting satellite for continuous meteorological survey.

P. G. Masefield (Managing Director, Bristol Aircraft Limited, *Fellow*): He felt that a possible product of guided flight in the civil direction might be the evolution of some way of relieving the greatly over-burdened pilot of the heavy task put on him today. If the pilot could be used as a monitor he could be more efficient, particularly during landings, compared with attempting to fly an intricate flight pattern in bad weather when approaching the airport. So perhaps, with its black

boxes, guided weapons might lead to civil applications one day in the direction of aiding the pilot.

They had had a fascinating start to the Guided Flight Section, especially on how the problems were being tackled and the major differences between the manned aeroplane and the guided weapon. But he thought they had not heard perhaps quite enough about the role of this guided weapon, and what the targets would be. If the manned fighter were gradually to disappear perhaps they had to look forward to the day when guided weapons, as they knew today, would not be in the picture either and it had been said by some people that—"it would never be as good as it was now" for the guided weapon business. In other words, the future requirements might not be so much guided weapons against bombers, but guided weapons against guided weapons. That was a tremendous task.

Mr. Serby: He thought that the pilot had become more and more a monitor already and he had tried to mention some ways in which he was moving in that direction. The pilot, however, did have to have something to monitor and what did this imply? Did it mean that he needed a certain amount of standby equipment, because if he were simply there to monitor the failure of something for which no alternative system was provided in the aeroplane then he was simply monitoring a disaster. This really brought them back to the point Mr. Morgan previously raised on the policy of standby or redundant elements in the system.

On the other point as to whether with increasing speed of attacking missiles and hence shortening of the interception time the guided missile would be put out of business; he did not think this at all likely. He thought the guided missile would continue to do its job provided the right amount of effort were put into its development; guided missiles could certainly be devised to defeat guided missiles. He had read in the paper that morning that the American Army had decided to devote $2,500,000,000 to just such a proposition.

L. W. Rosenthal (Co-ordinating Engineer, Design Dept., Saunders-Roe Ltd., *Associate Fellow*): Concerning the civil applications of rockets, some time ago, in fact in December 1934, a rocket-carrying mail was fired from the mainland to the Isle of Wight. This experiment, under Gerhard Zucker, was made in an endeavour to transmit mail from the Lymington area to the Isle of Wight. Unfortunately the flight was abortive.

One of Mr. Serby's figures showed the comparative phases of development of both aircraft and missiles. It was noticed that he gave no time scale. Would Mr. Serby make some comments on the differences and on any improvements in the development time which might be expected in the future?

Mr. Serby: He deliberately did not put a time scale on this, although it could form the basis of another lecture if someone were brave enough to do this.

S. Scott Hall (Scientific Adviser, Air Ministry, *Fellow*): In the figure which Mr. Serby showed, dealing with the growth factor, was he right in assuming that the curve referred only to a particular group of missiles? He believed that the growth factors for other groups were very different from those shown in that curve.

Mr. Serby: The curve was definitely restricted to weapons of the kind he was then discussing, namely air-to-air and current surface-to-air weapons.

A Speaker: Were they not being short-sighted and out of date by going into guided missiles? Ought they not perhaps to have a Space Flight Section?

Sir George Edwards: They had joined forces for a Symposium with the Interplanetary Society at the College of Aeronautics at Cranfield in July 1957. He believed that it was in the terms of reference of this Guided Flight Section that it should include the general approach to this.

Marcus Langley (Tiltman Langley Ltd., *Fellow*): Were they to have an early opportunity of discussing the other major problems of remotely guided weapons? They had heard a great deal this evening about the "little black boxes" but there were also the questions of construction, materials, propulsion, guidance, and the influence on these of the ambient atmosphere, whatever that might be, in the course of flight. Were these matters to be discussed at future meetings, please?

Sir George Edwards: The proposals would be recommended to the committee that controlled the Guided Flight Section. He was sure that if something had not already been done, it would be.

He would like to make one other comment, and that was that the interest in this subject was shown in the fact that, although there were only 150 members registered in this Section at present there were over 300 there to listen to Mr. Serby. That, he thought, was a visible sign that the paper excited their interest.

They appreciated very much the trouble Mr. Serby had taken and the work he had put into this lecture; it was an honour that he had agreed to deliver it.

Thurstan James (Editor of "THE AEROPLANE") *Contributed*: No reference was made to the Mayo Composite aircraft. Surely this was a most notable instance of the "staged" aircraft; it was fascinating to think what might have been achieved by incorporating a "satellite" in the "Mercury."

As regards the aircraft with movable wings, there could be little doubt that the classic example was Henry Mignet's Pou-du-Ciel. He agreed, of course, that it did not prove successful but it was a case of using an articulated front wing to provide control. There had been other machines in this field and a noteworthy case was the C 19 Autogiro which, after all, was an aeroplane with conventional specification except that a rotating wing was substituted for the fixed surface. Control was obtained by altering the place of rotation.

Mr. Serby: He agreed that the Mayo Composite Aircraft—a brilliant technical achievement of its day—was certainly a clear and early example of staged flight in manned aircraft. It did not however carry this principle quite as far as he had in mind, inasmuch as the part that was discarded was in fact a manned aeroplane which was brought safely back to earth and was not merely a collection of empty tanks which was jettisoned.

Recent Advances in the Design of Aircraft Tyres and Brakes*

by

H. W. TREVASKIS, A.F.R.Ae.S.

(Director of Development, Central Research Division, Dunlop Rubber Company)

1. Tyres

Ten years ago take-off speeds rarely exceeded 130 m.p.h. and the maximum inflation pressure used in aircraft tyres was about 120 lb./in^2. Today tyres have to cater for speeds up to 230 m.p.h. and pressures of 350 lb./in.^{2}. The increased requirements have produced serious problems of heat generation within the tread and carcass of tyres, which, if not solved, result in disintegration. Fig. 1 shows the effect of speed on tyre temperature and also, the effect of lightening the tyre construction.

Beyond the speed range shown, the temperature rises rapidly and tyre failures would occur. To meet these conditions, improved materials with lower hysteresis losses, and capable of operating at higher temperatures, have been produced. Control can also be obtained by modifying casing cord angles, reducing casing and tread thicknesses and so on.

To achieve the needed improved performance, a test machine is used which operates on the tyre-to-tyre principle. A maximum speed of 300 m.p.h. is obtainable, and the tyres can be loaded up to 17,000 lb. Two tyres can be run under load in contact, or can be bump loaded together, or any combination of these conditions, thus taxying, take-off and landing can be closely simulated. The power to drive this machine is obtained from a Rolls-Royce Merlin aero-engine, which provides the flexibility of power and speed necessary for such tests. It is also on this machine that the standing wave developed at high speed can be studied. Fig. 2 shows a typical wave, caused by high frequency oscillations within the structure of the tyre.

The standing wave creates such high stresses, that the life of the tyre is drastically reduced. The solving of this problem is difficult and a considerable amount of work is being done to achieve improvements, by modifying tread contours, casing cords and casing cord angles, and reducing the mass of the tyre, so that the natural frequency of vibration is increased.

Considerable changes have taken place in the materials used in tyre construction. The change to Nylon is important in this field. Nylon is the more usual type of cord used in aircraft tyres today. It has high resistance to fatigue and impact, but has the disadvantage that it stretches more than Rayon.

It is the most practical material so far tested for aircraft tyres. The problems of sidewall and tread groove cracking caused by high stretch have been largely overcome with the introduction of improved crack-resisting compounds. Improvements are anticipated from stronger Nylons which are now coming into use. In Fig. 3 the strength of present Nylon is compared with other materials.

Taking existing Nylon at 100 per cent, it will be seen that the strength of present day Rayon is of the order of 40 per cent on a weight basis. It will also be seen that the new Nylon is about two to three times as good as Rayon. Except for steel cords, Nylon is superior on a strength/volume basis. Steel is interesting because its high strength/volume ratio permits considerable reduction in bulk of a tyre, and could result in economy in rubber usage. Thus steel casings are not so heavy as might at first appear. There are, however, manufacturing problems associated with the use of steel cords, and on these we are now working.

It should be noted from Fig. 4 that Nylon tyres are not only 7 to 15 per cent lighter, but are about 60 per cent stronger than Rayon tyres, and thus have greater resistance to impact fracture. This point is very valuable in a tyre, which has so much deflection, and I would venture to say that impact fracture of aircraft Nylon tyres is almost unknown.

Although the initial cost is greater, civilian operators are using Nylon tyres remoulded three and four times, and they are therefore cheaper in the long run. The development of the materials mentioned has been

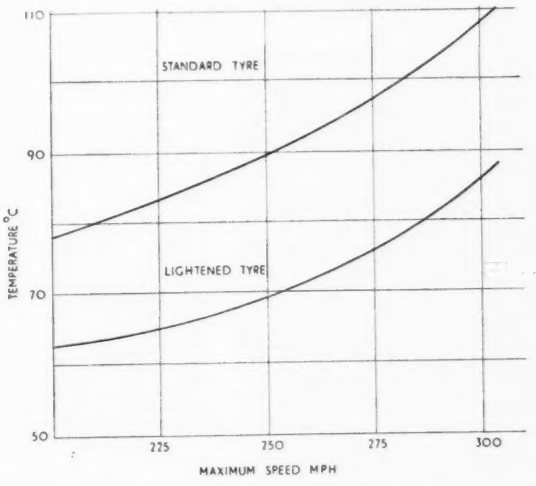


FIGURE 1. Effect of speed and tyre construction on tyre temperature.

*A Section Lecture given to the Society on 26th February 1957.

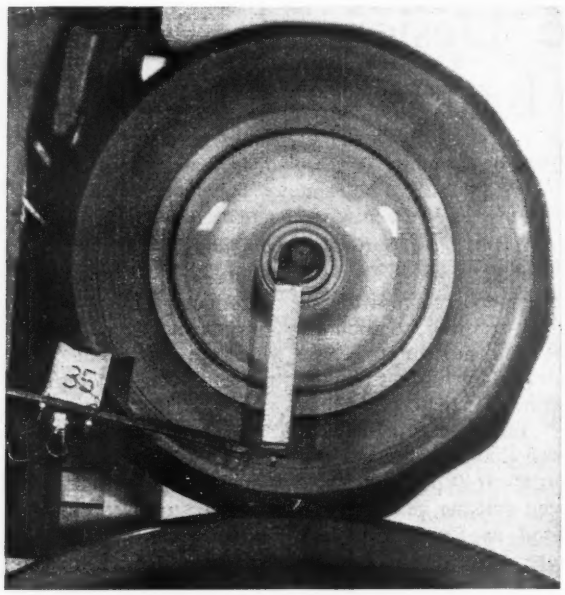


FIGURE 2.

extremely valuable to the tyre designer in changing from the large, relatively thin and flexible, low pressure tyre, to the small section, relatively thick and stiff high pressure tyre. The use of Nylon has enabled the designer to keep high pressure tyre thicknesses to a minimum and thus retain a high degree of flexibility. The introduction of high pressure tyres has brought changes of great importance and value to the aircraft designer. These benefits are shown clearly in Fig. 5.

This is a comparison of tyres from the 80 lb./in.² pressure group, and the 320 lb./in.² pressure group of the same load carrying capacity. The space required

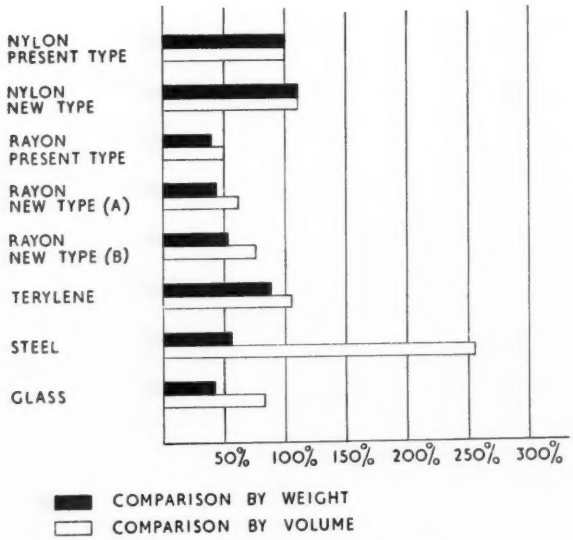


FIGURE 3. Comparison of cord strength

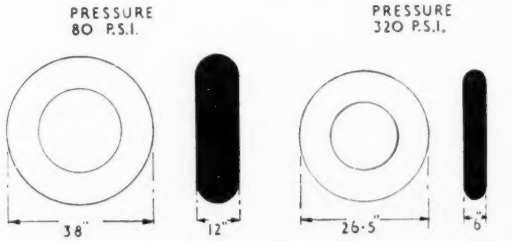
Aircraft	*Tyre weight*		*Bursting strength*	
	Rayon	Nylon	Rayon	Nylon
Freighter	100%	87%	100%	156%
DC-3	100%	85%	100%	163%
Dove	100%	93%	100%	160%
Heron	100%	86%	100%	169%

FIGURE 4. Chart showing comparison of rayon and nylon tyres.

for stowage is much less and in this instance there is a reduction of 75 per cent in bulk of tyre and wheel. An equally important gain has been achieved in the tyre weight, the saving being approximately 60 per cent. The large increase in the load carried per pound of tyre from 150 to 370 ib. and the considerable increase in the ground contact pressure from 100 to 350 lb./in.² will clearly indicate the extent of the tyre designer's problems.

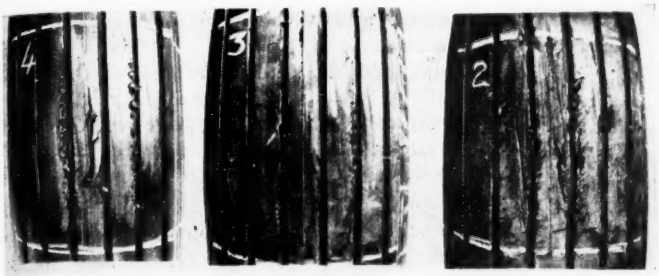
High ground contact pressures have caused considerable problems of rapid tread wear, flint cutting and other tread damage. It has been necessary to develop new tread compounds to meet with the need for resistance to wear, and work proceeds constantly to improve the resistance of treads to cutting and chipping damage. A test machine has been devised to produce the type of damage normally seen in service. The machine consists of a specially prepared surface of concrete with embedded flints which is dragged under a loaded tyre, which is locked against rotation. Fig. 6 shows the damage caused by the flints to various tread compounds. Results of these tests are reasonably conclusive. Materials, such as Polyurethanes, which might be expected to give good results, do not stand up to very high slip cutting and chipping. So far, the development of the natural rubber compound has, in this country, kept ahead of any of the processible synthetic materials.

The importance of tread influencing weight reduction is appreciated from the fact that compounded rubber represents about 75 per cent of the cover weight and the Nylon only 17 per cent. If longer life can be obtained from use of improved materials in the tread it can obviously be much more effective in reducing



100%	Relative bulk	25%
84	Tyre weight (lb.)	34
150	Pounds load per lb. of tyre weight	370
100	Ground contact pressure (p.s.i.)	350

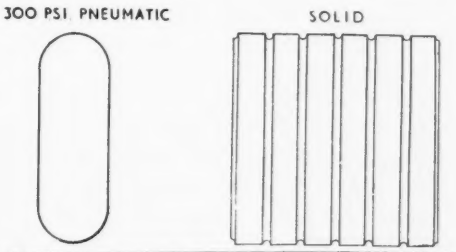
FIGURE 5. Effect of high pressure tyres on tyre characteristics. (12,500 lb. load capacity)



Superseded type Latest improved type

Natural rubber compounds Polyurethane type

FIGURE 6. Tread wear tests.



61	Weight (lb.)	168
300	Contact pressure (p.s.i.)	300
100%	Width	300%
1·6	Tyre Deflection (in.)	0·25

FIGURE 7.

weight than any improvement in the Nylon. While on the subject of high inflation pressures, this often raises the question of the practicability of solid tyres. Fig. 7 shows a comparison between solids and pneumatics for a high speed fighter.

It will be noted that the solid tyre will be three times the width and three times the weight, and has a very small deflection. In addition, inertia difficulties are created, and the undercarriage designer's problems would be considerably increased by the almost complete lack of deflection. In effect, the tyre filled with high pressure air is still a much better cushion and spring than the solid one. It is obvious that an enormous amount of development, probably requiring quite revolutionary materials, is necessary before solid tyres are to compete with pneumatics.

The continuous development of tyre tread patterns is aimed at producing tyres which will have the best possible wear life at the lightest weight and, which will give a good friction value on wet surfaces throughout their life. The modern circumferentially ribbed tyre illustrated in Fig. 8 meets present-day conditions better than any other. It has been found to have friction values comparable with *new* block pattern tyres. The latter wear unevenly, and are not so generally efficient in life and grip, because of what is known as "heel and toe" wear. Experiments have been made with dimple and knife-cut treads. The type of dimple tread illustrated has been developed to eliminate the risk of throwing stones, and it does not offer any significant advantage with regard to wear.

Up to the present, high braking reactions on aircraft tyres have resulted in knife-cut patterns, as illustrated, wearing unevenly, with consequent loss of efficiency. These experiments, however, are still in progress.

For use on ice, the most commonly attempted form of ice grip tread is that incorporating steel wire coils, as shown in Fig. 9. No very clear indication of their practical service value is available. It is probably not very good and they have the disadvantage that bits of metal come loose and may severely damage the aircraft. Development work is done on a rotating drum tyre testing machine and a layer of ice is produced around the drum surface. The drum is rotated at 15 m.p.h. and water is sprayed on the ice surface. The tyre is loaded on to the drum and the torque required to lock the tyre is measured.

Figure 10 shows some of the tyres tested and the work has proved the desirability of having:—

(*i*) A pattern with large circumferential and lateral grooves.

(*ii*) A very hard tread cap.

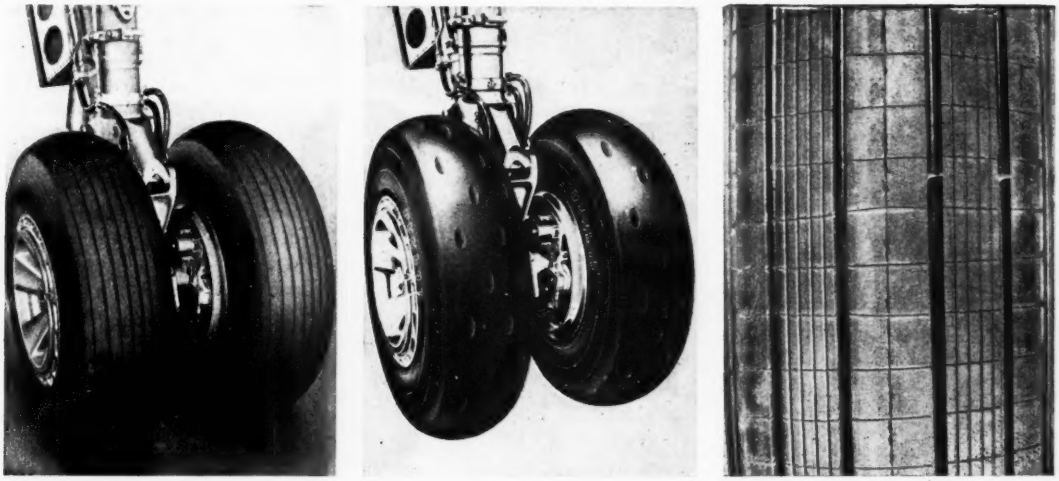


FIGURE 8.

(*iii*) Steel inserts securely fixed in the tread.
(*iv*) Low or medium pressure.

Although without recourse to steel inserts, friction values have been increased from below 0·015 to 0·12 and above; these values, while representing an enormous advance, are not adequate, and would probably not be maintained in service, particularly if the tyre were operated on ice-free runways, tending to wear and to modify the tread surface.

A modern development has been the tubeless tyre for aircraft. Satisfactory service tests have been made in this country on Meteor aircraft. Tubeless tyres are also operating on the Viscount 800 and Britannia 300, in addition to military types. Fig. 11 shows a section through a tubeless tyre, and a standard tyre. Basically, the tyres are identical, except that the tube is replaced by a lining of rubber inside the casing. The beads are designed so that under all loading conditions, they remain as a tight fit on the rim.

With the tubeless tyre, the following advantages can be obtained:—

On weight, an average of about 7½ per cent saving, or approximately half the weight of a normal tube.

They are cooler running by about 10°C., which is valuable.

Permeation losses are less.

Danger of deflation due to punctures is less. Deflation is rapid with tubed tyres, but is slower with tubeless. A tubeless tyre which had a number of nails driven through it lost only a few pounds pressure in 24 hours.

Tube troubles are eliminated, and this becomes particularly important on small high pressure tyres when the brake heat may become critical to the inner tube.

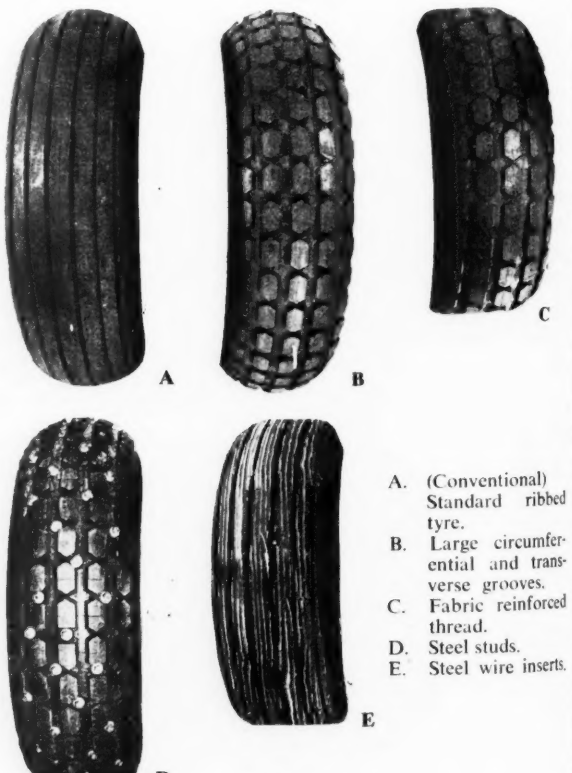
The tubeless tyre also has the advantage of giving the wheel designer great freedom in providing for the inflation valve, as compared with the tubed tyre. This will be noted from the figure which shows clearly that the conventional tube valve may, in some circumstances, restrict the diameter of the brake. The main difficulty is to maintain both the bead of the tyre and the rim in good condition, free from damage and foreign matter, to prevent air leakage. Tyre presses have been developed to facilitate removal and to minimise the possibility of damage to the rim and the beads of the tyre.

At present, furthur improvements are necessary to keep pace with the rapid development of aircraft to fly at supersonic speeds. To go to extremes, we are now asked to produce tyres which will be capable of withstanding temperatures of 250°C. An experimental tyre has been constructed of steel and heat resisting rubber. All materials used in its construction are able to withstand these temperatures.

Figure 12 shows the great difference between the operating characteristics of commercial vehicle tyres and aircraft tyres. Both the tyres shown carry a load of 12,000 ib. The main striking differences are the envelope size and load carried per pound of tyre. Figures like this emphasise the exacting demands made upon the aircraft tyre designer.

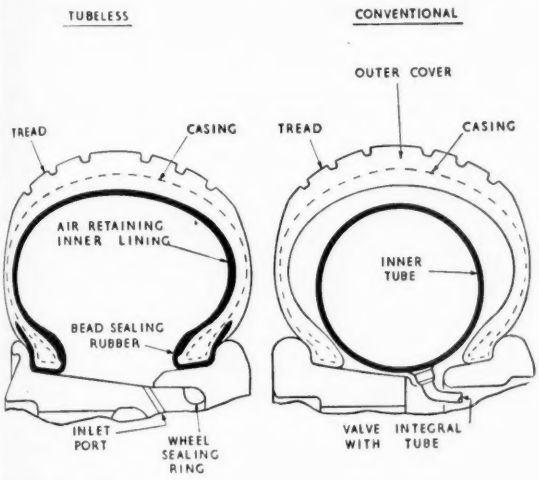
There is no doubt that great advances have been, and will continue to be made, but I feel that most of the future improvements will be derived from the discovery of better materials and, in fact, will only be a continuation of what has been happening over the past few years.

FIGURE 9.



A. (Conventional) Standard ribbed tyre.
B. Large circumferential and transverse grooves.
C. Fabric reinforced thread.
D. Steel studs.
E. Steel wire inserts.

FIGURE 10.



Tubeless valve arrangement.

Conventional valve arrangement.

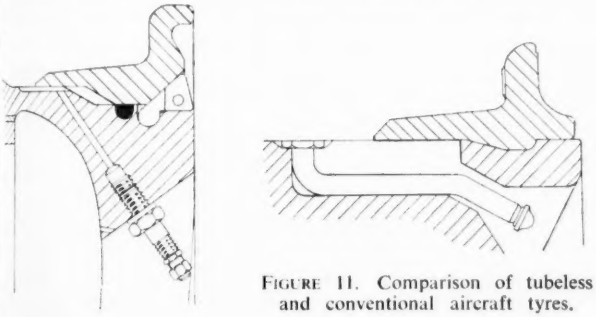
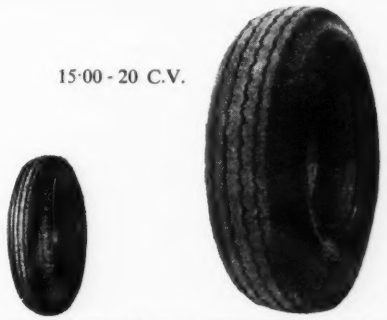


FIGURE 11. Comparison of tubeless and conventional aircraft tyres.



34	Tyre weight (lb.)	308
265	Inflation pressure (p.s.i.)	105
352	Load (lb.) per pound weight of tyre	39
320	Contact pressure (p.s.i.)	135
170-200	Speed (m.p.h.)	Up to 60

FIGURE 12.

2. Brakes

The chief function of the brake is, of course, to stop the aeroplane within a specified distance. It must not only provide a reasonably steady decelerating force, but must also absorb or dissipate most of the Kinetic Energy. The Energy is converted into heat through the medium of friction at a very high rate. To decelerate an aeroplane by means of friction forces applied at the ground, either by locking the wheels or by using some form of skid, would expose the occupants and the structure to a wide range of decelerations, due mainly to the variation in the coefficient of sliding friction with different runway surfaces and weather conditions.

One of the advantages of a wheel brake is that the mechanism of sliding friction is transferred from the tyre/ground contact area to the brake, where it can be used under controlled conditions which are independent of the runway state. By this means, and by control of the braking intensity, it is ensured that the decelerating force produced by the brake can be transmitted to the ground, using the higher coefficient of friction between the tyre and the ground.

Energy absorption requirements have increased considerably over the past few years and Fig. 13 shows the amount of energy absorbed in a present day brake compared with an earlier design. Both of the brakes are designed to fit within the space available in a 16½ in. diameter wheel. The energy capacity of the current brake has been increased over that of the earlier version by 102 per cent under normal conditions and, by 144 per cent under emergency conditions.

The lining materials used for some years with drum and disc brakes gave good service if they were not abused. They do, however, fall short of desirable standards in some respects for present day performance requirements. It is often found that a material may give a commendably low rate of wear, but will give a very high friction coefficient, statically and at low speeds, as shown by the upper curve in Fig. 14. Others give a lower and more acceptable slow speed friction coefficient, but the rate of wear is aggravated, as shown by the lower curve.

Many of these conventional organic materials suffer deterioration throughout their lives, and they are prone

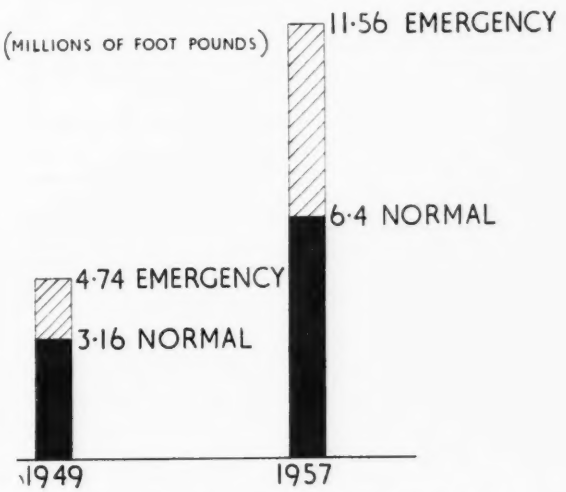


FIGURE 13. Brake energy capacity for 16½ in. wheel.

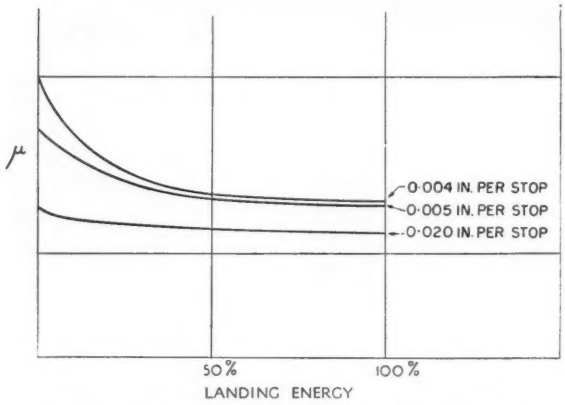


FIGURE 14. Alternative lining materials friction and wear.

to show measurable scatter in friction characteristics, from batch to batch of nominally the same composition. To maintain a higher intensity, and reduce costs of aircraft operation, the service life of brake linings for civil aircraft must be such that lining replacement coincides with other maintenance checks, preferably with no time penalty.

The factors which lead to a high rate of wear for a given lining material are:—

(*i*) High rubbing speed.
(*ii*) High surface pressure.
(*iii*) High surface temperature.
(*iv*) Rubbing surface deterioration.

In designing for low wear, the problem is to reduce these factors to a minimum. The surface temperature is influenced by rubbing speed and lining pressure. Temperature limitation can be achieved by using a high conductivity heat sink material, such as copper, and as large a swept area as possible.

For a brake built into, and acting directly on, the wheel, as most aircraft brakes do, the rubbing speed is determined, within narrow limits, by the aircraft speed. It follows that it is important not to overwork the surfaces of either the lining or the heat sink, and the rate of input of energy must be restricted to enable the materials to absorb the conditions. Fig. 15 shows the difference in rate of wear for heat sinks of different materials for various horse power loadings.

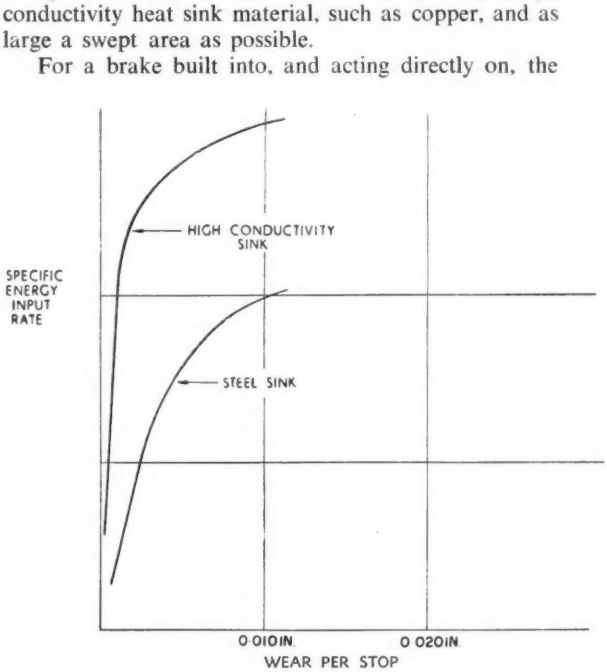


FIGURE 15.

The use of a high conductivity material for the heat sink is not advantageous, due to its high weight, but this disadvantage may be offset by the considerable extension of the lining life. Unfortunately, it also increases the bulk depth of a disc brake, since the material has a lower melting point, which limits the temperature to which it may be allowed to rise. More material has then to be provided to absorb the same energy.

To reduce the surface pressure, the area of the linings may be increased, and to reduce the surface temperature, the swept area of the heat sink can also be increased. In most cases, the latter may only be done by splitting the heat sink into a greater number of discs. These measures will increase the brake weight and the alteration to the heat sink increases the brake depth, since the depth allowance for incompletely used linings has to be multiplied. The life may be increased by fitting thicker linings and then it is necessary to provide increased travel of the operating mechanism. Space is limited and cases have already occurred where it has been impossible to provide conventional brake linings of adequate life, together with a suitable wheel spoke structure, within the space available. These factors show that for some applications, the present limiting working conditions of the conventional lining materials have already been reached, and even exceeded.

To keep up with, and if possible ahead of, the demands for greater performance and energy capacity, brake design may be shown to have advanced in a logical sequence. With a drum brake, all the heat is passed into the drum, as indicated by the arrows in Fig. 16, through less than half of its total surface area, the inner surface only being used.

The next step has been the development of the disc brake, in which all the heat is transmitted into the heat sink through the greater part of the disc surface, since both sides are used. This enables a much higher rate of energy conversion to be achieved, than with a drum of similar capacity. The logical step forward was to attempt to pass some of the heat into, and through, the linings themselves, thus making use of the heat capacity of the brake mechanism. The organic lining material of the conventional resin-bonded type is a low heat conductor and is susceptible to chemical changes under the action of heat. After considerable research, an inorganic lining has been evolved, which has good thermal conductivity.

As indicated by the arrows in Fig. 17, part of the heat generated is passed into the disc or rotor and part into, and through, the inorganic lining to the stator, on which it is mounted. (The stators are shown in Fig. 19)

This has the effect of reducing the surface

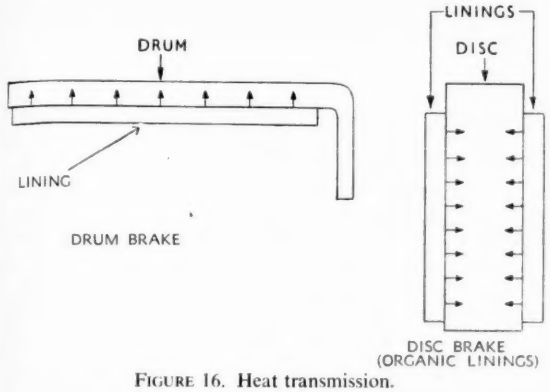


FIGURE 16. Heat transmission.

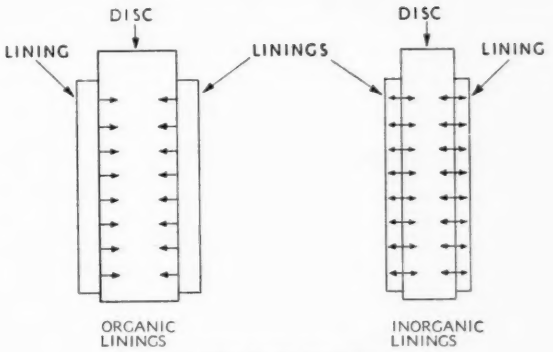


FIGURE 17. Disc brake heat transmission.

temperature of the disc and of the lining. For a given energy capacity, the disc may be made thinner, since it has less heat to absorb. The linings conduct heat and, in so doing, the surface temperature of the disc is reduced. This is the major factor in reducing the rate of wear, making possible thinner linings with longer life.

The combination of thinner discs and thinner linings permits the depth of the brake in the wheel envelope to be considerably reduced, and this may be regarded as a major advance, since it directly helps to obtain space for a lighter wheel spoke structure.

Inorganic brake linings have, so far, exhibited a marked stability. The friction coefficient is well maintained up to high rubbing speeds and overall heat sink temperatures. The rate of wear is considerably less than that of organic linings. The scatter in friction characteristics from batch to batch of material is small, thus reducing the scatter factors on peak torques. The wear characteristics of the two types of linings are compared in Fig. 18, showing the improvements that may be achieved at higher loadings with the inorganic lining.

An exploded view of an inorganic brake is shown in Fig. 19. The discs with drive tenons on their outer edges can be seen sandwiched between the stators carrying the linings. The operating cylinders are in the torque plate shown on the left, and on the right is the thrust ring which reacts the brake pressure. The brake torque is transmitted by tenons on the inner edges of the stators into the splines on the torque tube. This is the brake represented by the example for 1957 in Fig. 13.

As a measure of the advances which have been made, the weight of the 1949 brake was 20 lb./million ft. lb. of normal energy, whereas the brake shown in Fig. 19 weighs only 13 lb./million ft. lb.

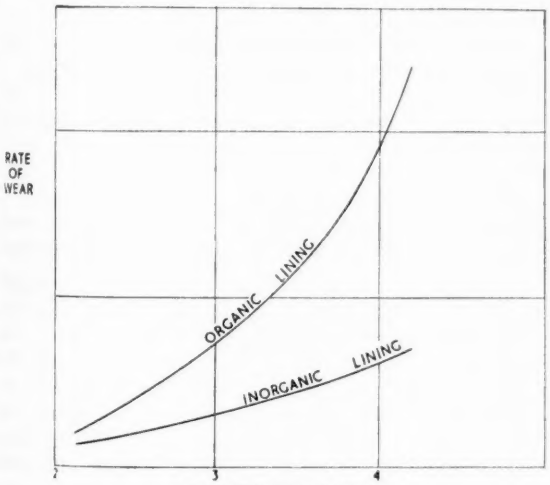


FIGURE 18.

PERFORMANCE DURING REJECTED TAKE-OFF

The extreme braking which is required for the rejected take-off represents the most severe condition which the brake is required to meet, because the brake rubbing speed initially is considerably higher than it is in a normal landing, and the energy to be absorbed may amount to double the normal landing requirements. The combination of high rubbing speed and high heat sink temperature causes excessive heating and wear of the linings. It is acknowledged that if the aircraft is stopped within a specified distance, the brake may be permitted, in this extreme case, to become unserviceable, but the aim is always to have a small margin in hand so that the aircraft can be handled until re-servicing is possible. Under these conditions, the rate of wear of organic linings is excessive, owing to thermal deterioration, and the friction coefficient may be seriously reduced below the average value obtained under normal conditions.

Inorganic linings are more resistant to extreme conditions and the friction coefficient, although somewhat reduced below the normal value, is well preserved to the end of the stop.

VARIATION OF FRICTION COEFFICIENT

In attempting to obtain constant performance of the friction elements over the full range of conditions, there are two approaches to be made:—

(1) Development of compatible rubbing material to extend the operating range.
(2) Use of a given material to its best advantage.

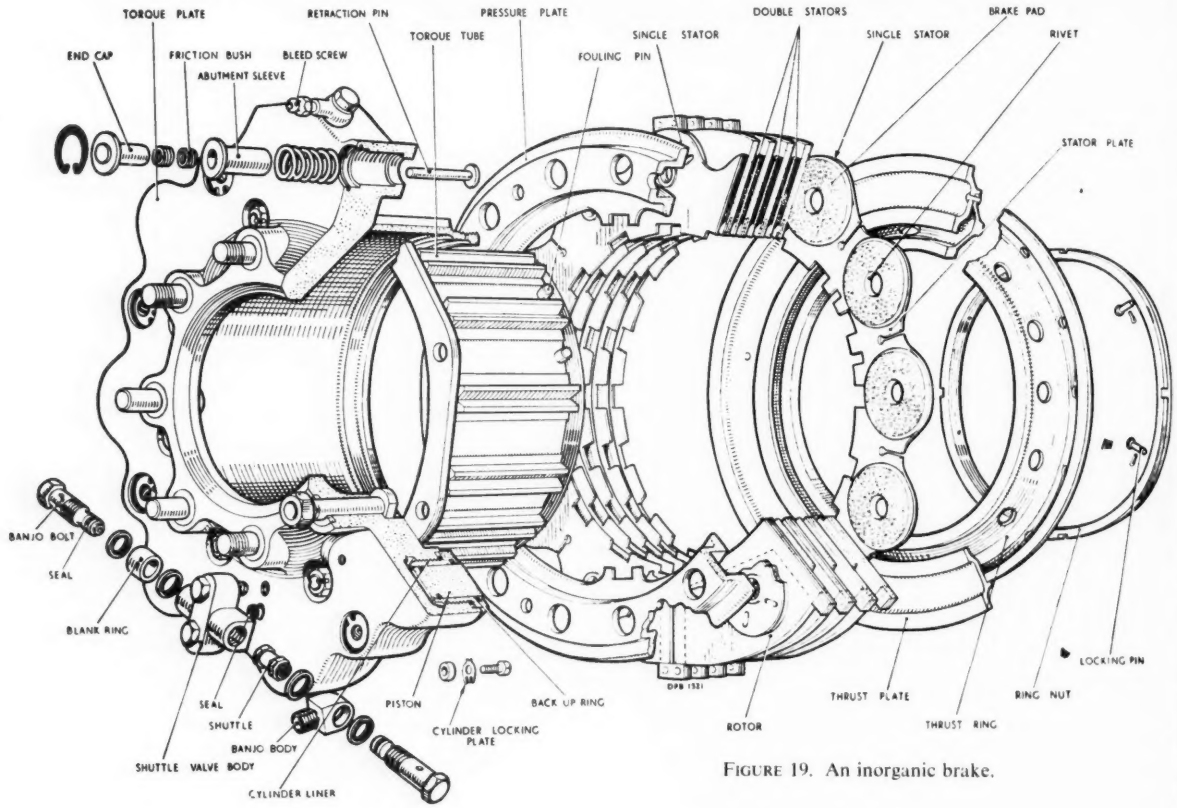


FIGURE 19. An inorganic brake.

Typical limits of operating conditions in practice are:—

(*i*) Rubbing speed—zero to 150 ft./sec.
(*ii*) Surface pressure—zero to 1,000 lb./in.^{2}.
(*iii*) Surface temperature from $-65°C$ to $+2{,}000°C$.
(*iv*) Surface condition which can be clean and dry, or rough and disintegrating.

Optimum design is aimed at producing a constant friction coefficient over the whole working range of these conditions. In practice, with some brake designs, it is difficult to raise the minimum value to more than one-third of the maximum, as may be seen from Fig. 20.

Extremes arise in the following ways:—

(*i*) Rejected take-off stops involve high rubbing speed, and high temperature, causing rapid wear.
(*ii*) In normal stops, normal friction is developed with moderate variation throughout the stop.
(*iii*) In low speed braking the discs have cool, clean surfaces and the friction coefficient approaches the full static value.
(*iv*) Lastly, the case of static torque such as may be required to hold engine thrust. Here, there may be considerable scatter due to variations in surface conditions, which may be clean and dry, or contaminated, or even distorted through previous use.

In designing to meet these extremes, we know that the *maximum* dynamic and static friction values should have little scatter for a given pad material. The brake force under these conditions may determine the structural strength requirements. The peak dynamic values will generally occur on cool surfaces and at low rubbing speeds. In conditions involving more work on the friction pads the friction will be reduced, and aircraft designers are now demanding high performance under rejected take-off conditions.

Also, static brake torque, sufficient to hold the aircraft against very high engine thrust becomes a critical requirement for some aircraft. In this case, due to the drop in friction in the more adverse operating conditions, as shown in Fig. 20 at 200 per cent energy and the possible drop in friction caused by adverse surface conditions, as shown by the lower value of friction at zero energy, a higher operating pressure must be available than would be required for normal braking.

Unless special precautions are taken, the higher pressure could be used on low speed taxying when the maximum coefficient of friction is produced, giving rise to brake forces far higher than are necessary for the control of the aircraft, and which would have to be considered in the structural design of the brakes and the aircraft. These precautions (such as separate switches and so on) are not popular and are only used where unavoidable. If the excess pressure requirements are of a large order, it follows that severe weight

penalties will be involved. These may apply not only to the brakes, but to the aircraft undercarriage, both main and nose.

It is clear, therefore, that a primary aim in modern brake design is in getting the lower limiting value of the coefficient of friction as high as possible.

Figure 21 shows an example of how a brake has been developed to give an improved overall performance. A minimum required brake torque was specified in each of the emergency, normal and static cases, and these requirements are shown as heavy horizontal lines in three of the lower diagrams, which are drawn to a common scale. The left hand columns in each of the lower diagrams represent the performance of the first experimental brake. The correct emergency torque has been obtained, but at the expense of a high operating load, which produces more torque in the normal energy condition than is required, together with a high peak torque. In the graph, the lower curve of mean μ against energy, reflects the friction characteristics of this brake. Stage two is obtained by adjusting the lining areas, to increase the friction at emergency energy. The friction at normal energy is also increased, although to a smaller extent, while the static μ is unaffected.

The net result is indicated in the middle columns of each of the lower diagrams. The required emergency torque is now obtained with a reduced operating load, thus ensuring that the normal torque is not so excessive and the maximum peak and static torques are considerably reduced. By further refinement of the design, the third stage is reached and with this an even lower operating load is possible as shown by the right hand columns in each of the lower diagrams. This load is now determined by the minimum static torque requirement.

The improvements achieved by the development from Stage 1 to Stage 3 are: —

(*i*) Reduction in peak torque and operating load of 45 per cent.

(*ii*) More consistent performance throughout the whole range of conditions, the ratio of maximum to minimum having been reduced from 4·5 to one down to 2·3 to one.

It is characteristic of current brake lining materials

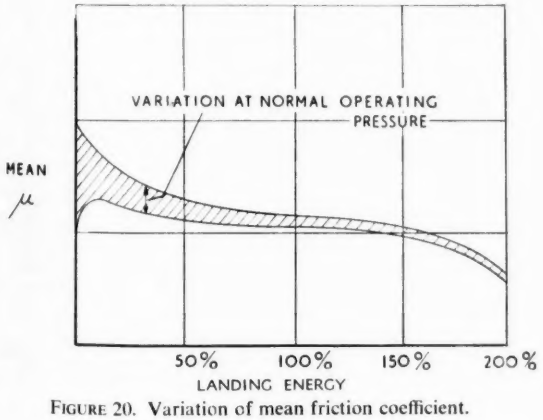


FIGURE 20. Variation of mean friction coefficient.

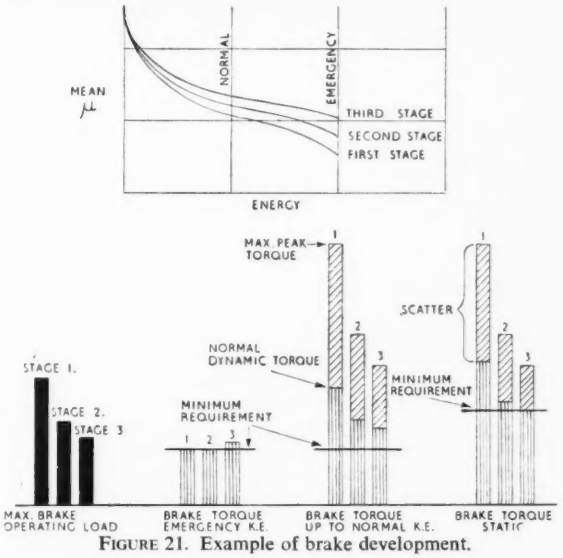


FIGURE 21. Example of brake development.

that a gradual loss of friction occurs as the severity of the operating conditions is increased to a critical point, beyond which the friction deteriorates more rapidly and the rate of wear increases substantially. To design within a safe margin, from this critical point, it is becoming necessary with high performance brakes, to provide larger areas of lining surface. This means greater coverage of the disc area with linings and employing larger numbers of discs in the brake. Some current brakes have linings approaching 90 per cent coverage of the swept disc surface. Complete coverage would not provide escape channels for lining wear particles, and loss of friction would result.

TESTS

Some mention must be made of the test methods used to assist the designer. For development testing, standard test brakes are used in which the heat sink capacity and material may be varied, also the lining material and disposition. These tests provide such relevant design data as permissible surface pressure and rates of heat absorption for given rubbing speeds.

A new test machine recently brought into use enables the complete tyre, wheel and brake assembly to be tested as a unit. The assembly is mounted on a travelling carriage and forced against an inertia drum by means of a pneumatic ram. The drum weight is adjustable and the speed may be varied through a wide range to enable tests to be carried out which are representative of aircraft conditions. With the help of extensive instrumentation, and the advantage of introducing the tyre into tests, a more complete picture of a brake's characteristics and performance is now obtainable.

In conclusion, although we seek to reduce still further the rate of wear of brake linings, and to improve their friction characteristics under extreme energy conditions, it is thought that the disc brake in its latest form has reached a high degree of development.

TECHNICAL NOTES

Standardised Polynomials for Curve Fitting

by

M. FINE

(*Rotol Limited*)

LAGRANGE'S INTERPOLATION formula can be used to obtain an approximate polynomial representation of a curve (derived empirically, or known otherwise) as well as to interpolate between isolated values of a function. In obtaining such an approximating polynomial, standardisation of the values of the independent variable has the advantage that many relevant quantities can be calculated and tabulated (or plotted, or both) in advance.

Suppose it is required to represent y, a function of x, by a polynomial Y_n of degree n in x over an interval $a \leqslant x \leqslant b$. Let $X=(x-a)/(b-a)$ so that X is the fractional distance of x from a; let $X_1, X_2, \ldots . X_n, X_{n+1}$ be $n+1$ different values of X in $0 \leqslant X \leqslant 1$; let

$$P_{i,n}(X)=\frac{(X-X_1)(X-X_2)\ldots.(X-X_{n+1})}{(X_i-X_1)(X_i-X_2)\ldots.(X_i-X_{n+1})}$$

the terms corresponding to $X-X_i$ being omitted. Then

TABLE I

x	$P_{1,3}$	$P_{2,3}$	$P_{1,4}$	$P_{2,4}$	$P_{3,4}$
0	1·0	0	1·0	0	0
0·02	0·8935	0·1711	0·8383	0·2931	−0·2106
0·06	0·7014	0·4619	0·5784	0·7306	−0·4732
0·10	0·5355	0·6885	0·3744	0·9984	−0·5616
0·14	0·3941	0·8560	0·2216	1·128	−0·5167
0·18	0·2753	0·9697	0·1117	1·149	−0·3769
0·22	0·1776	1·035	0·0370	1·087	−0·1746
0·26	0·0993	1·056	−0·0093	0·9653	0·0604
0·30	0·0285	1·040	−0·0336	0·8063	0·3024
0·34	−0·0075	0·9896	−0·0416	0·6280	0·5299
0·38	−0·0373	0·9117	−0·0382	0·4463	0·7253
0·42	−0·0558	0·8112	−0·0278	0·2744	0·8746
0·46	−0·0636	0·6930	−0·0140	0·1229	0·9681
0·50	−0·0625	0·5625	0	0	1·0
0·54	−0·0542	0·4248	0·0120	−0·0890	0·9681
0·58	−0·0404	0·2850	0·0201	−0·1414	0·8746
0·62	−0·0229	0·1485	0·0234	−0·1568	0·7253
0·66	−0·0033	0·0202	0·0214	−0·1368	0·5299
0·70	0·0165	−0·0945	0·0144	−0·0897	0·3024
0·74	0·0348	−0·1905	0·0033	−0·0197	0·0604
0·78	0·0501	−0·2625	−0·0105	0·0616	−0·1746
0·82	0·0604	−0·3055	−0·0245	0·1411	−0·3769
0·86	0·0642	−0·3142	−0·0361	0·2034	−0·5167
0·90	0·0595	−0·2835	−0·0416	0·2304	−0·5616
0·94	0·0448	−0·2081	−0·0369	0·2012	−0·4732
0·98	0·0183	−0·0829	−0·0131	0·0924	−0·2106
1·0	0	0	0	0	0

$P_{3,3}(x)=P_{2,3}(1-x)$ $\quad$ $P_{4,4}(x)=P_{2,4}(1-x)$

$P_{4,3}(x)=P_{1,3}(1-x)$ $\quad$ $P_{5,4}(x)=P_{1,4}(1-x)$

Received 23rd October 1957.

$P_{i,n}(X)$ is of degree n in X; it has the value one when $X=X_i$; it has the value zero if $X=X_j$ where $j \neq i$. Hence $\Sigma_i A_i P_{i,n}(X)$ is a polynomial of degree n in X which has the value A_i when $X=X_i$ and which, therefore, can be made to coincide with any polynomial of degree n in X by suitable choice of A_i $(i=1, 2, 3 \ldots ., n+1)$.

If y_i is the value of the given function y at $X_i=(x_i-a)/(b-a)$ then $Y_n=\Sigma y_i P_{i,n}(X)$ coincides with y at the $n+1$ points x_i. A different approximation, also of degree n, may be obtained by choosing different numbers x_i giving rise to different functions $P_{i,n}$; a more convenient method is to replace y_i by y_i+E_i with x_i, X_i and $P_{i,n}$ unchanged. In other words it is more convenient to keep x_i and X_i unchanged and let y, Y_n have different values at

TABLE II

x	$P_{1,5}$	$P_{2,5}$	$P_{3,5}$
0	1·0	0	0
0·02	0·7897	0·4387	−0·4153
0·05	0·5358	0·8929	−0·7651
0·08	0·3445	1·148	−0·8611
0·11	0·2045	1·250	−0·7757
0·14	0·1061	1·238	−0·5713
0·17	0·0404	1·144	−0·2989
0·20	0	1·0	0
0·23	−0·0216	0·8267	0·2920
0·26	−0·0297	0·6438	0·5515
0·29	−0·0289	0·4663	0·7626
0·32	−0·0228	0·3046	0·9136
0·35	−0·0430	0·1665	1·0
0·38	−0·0054	0·0571	1·0250
0·41	0·0024	−0·0238	0·9802
0·44	0·0081	−0·0739	0·8870
0·47	0·0112	−0·0974	0·7513
0·50	0·0117	−0·0976	0·5859
0·53	0·0099	−0·0797	0·4035
0·56	0·0063	−0·0493	0·2218
0·59	0·0017	−0·0121	0·0516
0·62	−0·0033	0·0247	−0·0932
0·65	−0·0077	0·0557	−0·2000
0·68	−0·0108	0·0762	−0·2610
0·71	−0·0118	0·0823	−0·2706
0·74	−0·0104	0·0716	−0·2271
0·77	−0·0064	0·0435	−0·1342
0·80	0	0	0
0·83	0·0083	−0·0545	0·1599
0·86	0·0173	−0·1125	0·3229
0·89	0·0253	−0·1630	0·4591
0·92	0·0300	−0·1914	0·5299
0·95	0·0282	−0·1785	0·4869
0·98	0·0161	−0·1013	0·2720
1·0	0	0	0

$P_{4,5}(x)=P_{3,5}(1-x)$ $\quad$ $P_{5,5}(x)=P_{2,5}(1-x)$

$P_{6,5}(x)=P_{1,5}(1-x)$

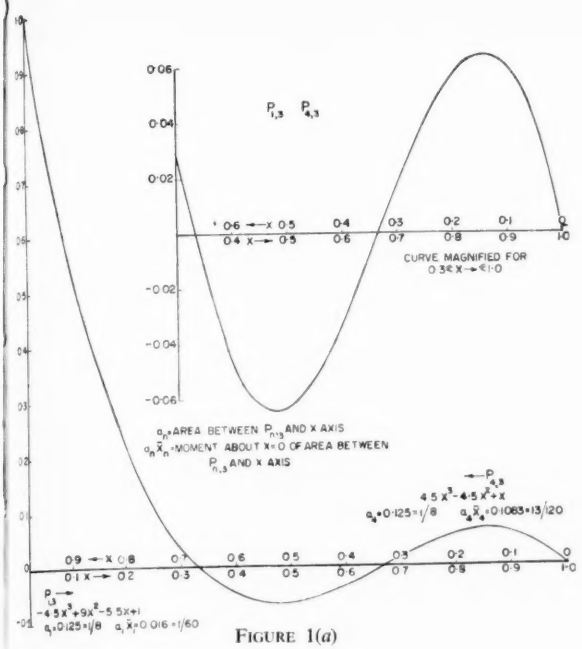

$P_{1,3}$ $P_{4,3}$
CURVE MAGNIFIED FOR $0.5 \leqslant X \rightarrow \leqslant 1.0$
a_n = AREA BETWEEN $P_{n,3}$ AND X AXIS
$a_n \bar{x}_n$ = MOMENT ABOUT X=0 OF AREA BETWEEN $P_{n,3}$ AND X AXIS
$P_{4,3}$
$4.5X^3-4.5X^2+X$
$a_4=0.125=1/8$ $a_4\bar{x}_4=0.1083=13/120$
$P_{1,3}$
$-4.5X^3+9X^2-5.5X+1$
$a_1=0.125=1/8$ $a_1\bar{x}_1=0.016=1/60$

FIGURE 1(*a*)

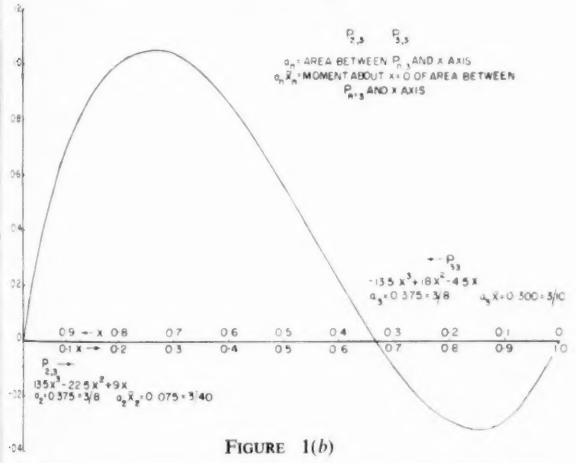


FIGURE 1(*b*)

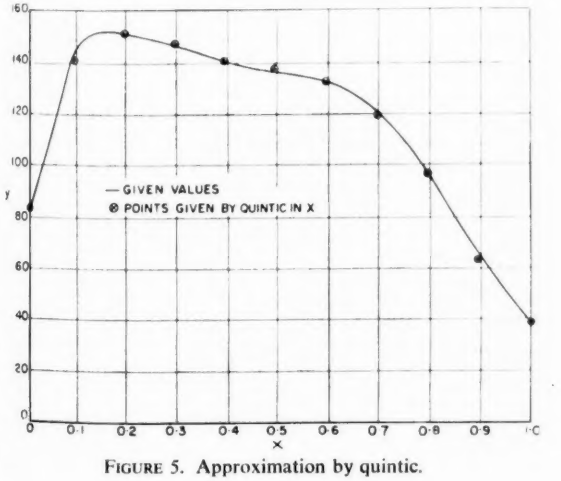


FIGURE 5. Approximation by quintic.

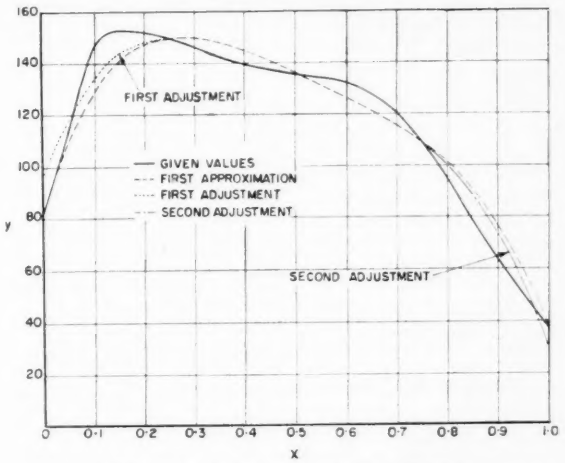


FIGURE 4(*a*). Approximation by quartic.

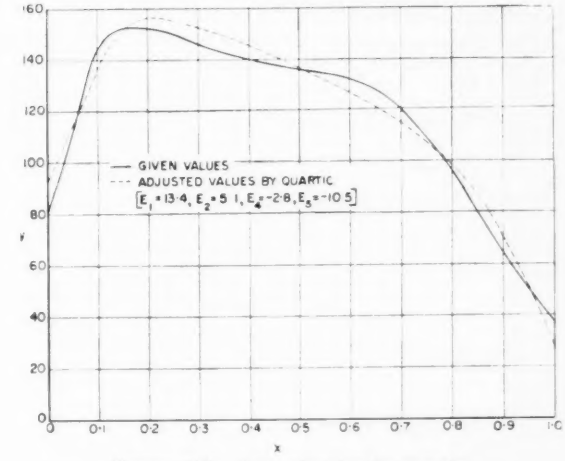
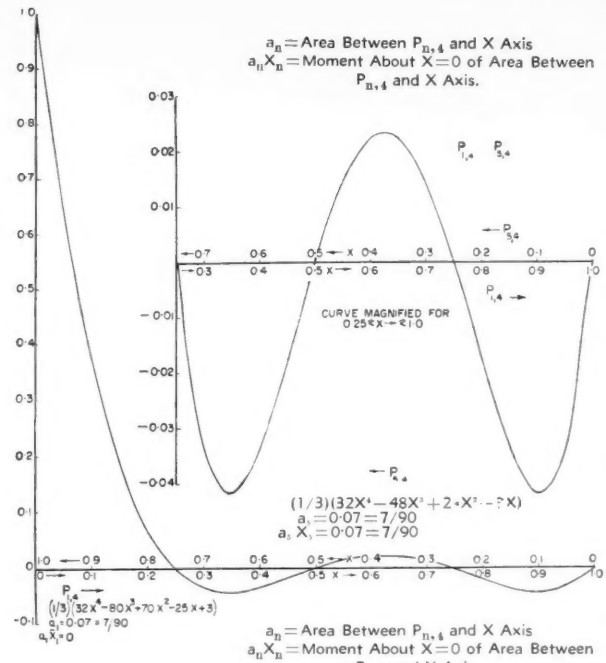


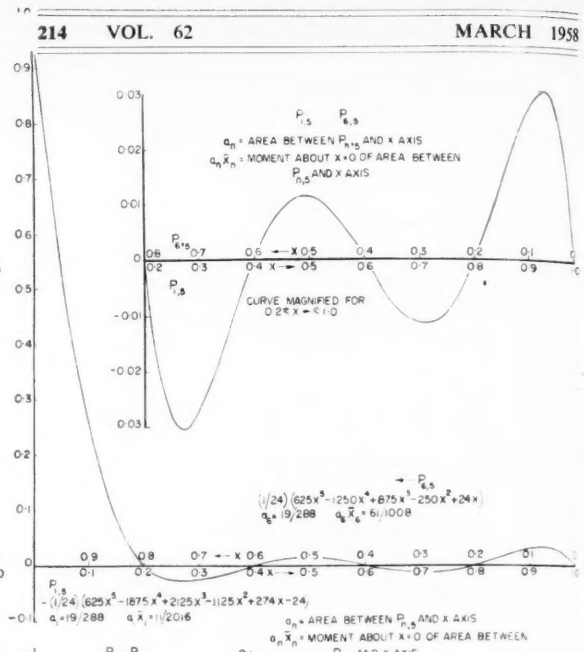
FIGURE 4(*b*). Approximation by quartic.

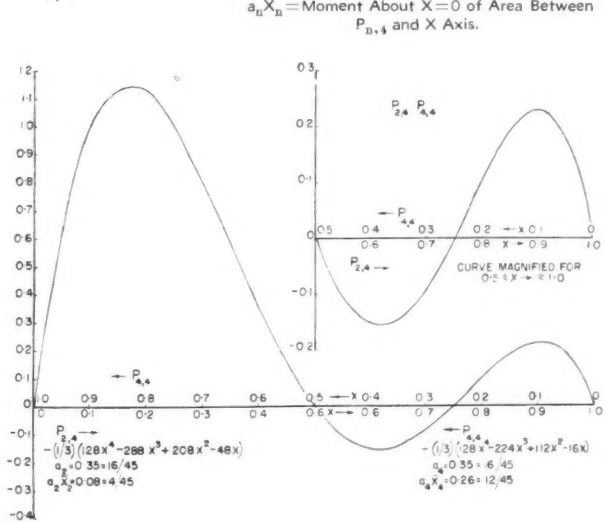
these points than to specify anew the values x_i for which y, Y_n coincide. This is because the functions $P_{i,n}$, once tabulated, may be used in all cases if X_i are fixed. Hence adjustments to Y_n are readily made by suitable choice of E_i; the degree of accuracy obtainable with a polynomial of degree n is readily assessed; simple properties of y, such as area, moment of area, and so on, are readily obtained if the corresponding properties of $P_{i,n}$ are tabulated.

Figures 1-3 show the graphs, and some properties of $P_{i,n}$ for cubics, quartics and quintics, the points X_i being chosen to divide $0 \leqslant X \leqslant 1$ into equal intervals. Fig. 4(*a*) shows a given function of X (polar moment of inertia of propeller blade section varying along its length), an approximation to the function by a quartic, and two adjustments to this approximation. These adjustments are chosen so as to equalise the greatest discrepancy on either side of (*a*) the first crossing point and (*b*) the last crossing point of the curves. Fig. 4(*b*) shows the result of equalising errors on either side of the second and fourth crossing points also. This process is quite simple and rapid once the $P_{i,n}$ are available. (Approximation by least squares is not so rapid.)

The first quintic approximation to the function is shown in Fig. 5.


a_n = Area Between P_{n+4} and X Axis
$a_n X_n$ = Moment About X=0 of Area Between P_{n+4} and X Axis.
CURVE MAGNIFIED FOR 0·25≤X→≤1·0
$(1/3)(32X^4-48X^3+2+X^2-?X)$
$a_1 = 0·07 = 7/90$
$a_0 X_0 = 0·07 = 7/90$
$(1/3)(32X^4-80X^3+70X^2-25X+3)$
$a_1 = 0·07 = 7/90$
$a_1 X_1 = 0$


a_n = AREA BETWEEN P_{n+5} AND X AXIS
$a_n \bar{x}_n$ = MOMENT ABOUT X=0 OF AREA BETWEEN P_{n+5} AND X AXIS
CURVE MAGNIFIED FOR 0·2≤X→≤1·0
$(1/24)(625X^5-1250X^4+675X^3-250X^2+24X)$
$a_5 = 19/288$ $a_5 \bar{x}_5 = 61/1008$
$-(1/24)(625X^5-1875X^4+2125X^3-1125X^2+274X-24)$
$a_0 = 19/288$ $a_0 \bar{x}_0 = 11/2016$


a_n = Area Between P_{n+4} and X Axis
$a_n X_n$ = Moment About X=0 of Area Between P_{n+4} and X Axis.
CURVE MAGNIFIED FOR 0·5≤X→≤1·0
$-(1/3)(128X^4-288X^3+208X^2-48X)$
$a_2 = 0·35 = 16/45$
$a_2 \bar{x}_2 = 0·08 = 4/45$
$-(1/3)(128X^4-224X^3+112X^2-16X)$
$a_4 = 0·35 = 6/45$
$a_4 \bar{x}_4 = 0·26 = 12/45$
$64X^4-128X^3+76X^2-12X$
$a_3 = 0·13 = 2/15$
$a_3 \bar{x}_3 = 0·06 = 1/15$
a_n = AREA BETWEEN P_{n+4} AND X AXIS
$a_n \bar{x}_n$ = MOMENT ABOUT X=0 OF AREA BETWEEN P_{n+4} AND X AXIS

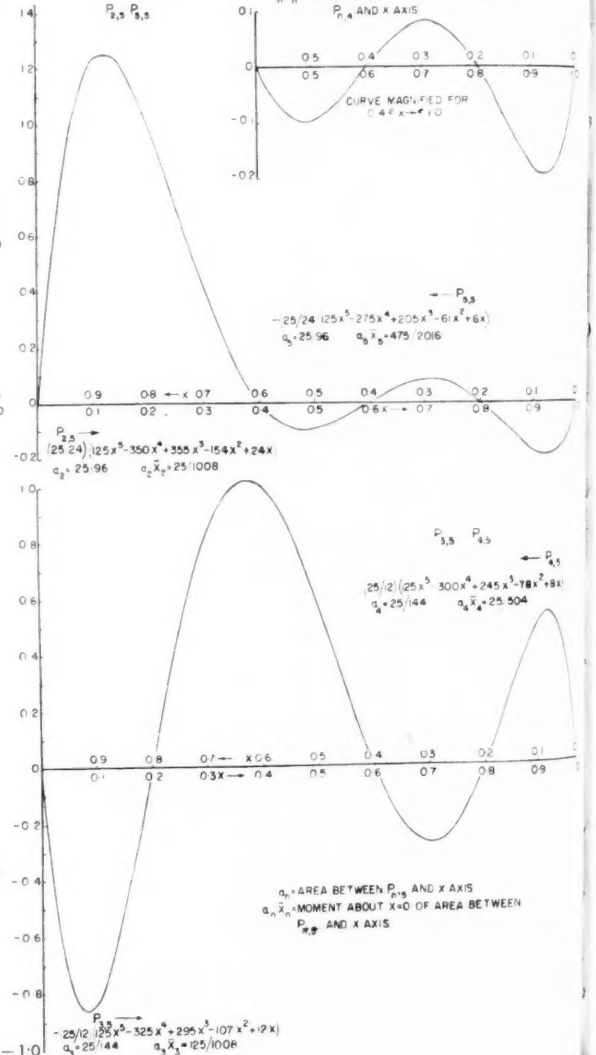

a_n = AREA BETWEEN P_{n+5} AND X AXIS
$a_n \bar{x}_n$ = MOMENT ABOUT X=0 OF AREA BETWEEN P_{n+4} AND X AXIS
CURVE MAGNIFIED FOR 0·4≤X→≤1·0
$-(25/24)(125X^5-275X^4+205X^3-61X^2+6X)$
$a_5 = 25/96$ $a_5 \bar{x}_5 = 475/2016$
$(25/24)(125X^5-350X^4+355X^3-154X^2+24X)$
$a_2 = 25/96$ $a_2 \bar{x}_2 = 25/1008$
$(25/12)(25X^5-300X^4+245X^3-78X^2+8X)$
$a_4 = 25/144$ $a_4 \bar{x}_4 = 25/504$
$-(25/12)(125X^5-325X^4+295X^3-107X^2+12X)$
$a_3 = 25/144$ $a_3 \bar{x}_3 = 125/1008$
a_n = AREA BETWEEN P_{n+5} AND X AXIS
$a_n \bar{x}_n$ = MOMENT ABOUT X=0 OF AREA BETWEEN P_{n+5} AND X AXIS

FIGURE 2(*a*), (*b*) and (*c*).

Note:—0·5. 0·7 and 0·8 should be recurring.

FIGURE 3(*a*), (*b*) and (*c*).

If $n \leqslant 5$ then an addition E_i to y_i at X_i is largely localised near X_i. If $n > 5$ we cannot take equal intervals in $0 \leqslant X \leqslant 1$ and still retain this desirable feature; the X_i must be crowded near 0 and 1.

If $X = \cos\theta$, $0 \leqslant \theta \leqslant \pi/2$, $\theta_i = (2i-1)\,\pi/2\,(n+1)$

$$T_{i,n} = \frac{(-1)^{(i-1)} \cos(n+1)\theta}{\cos\theta - \cos\theta_i} \Big/ \frac{n+1}{\sin\theta_i},$$

then $T_{i,n}$ is a polynomial of degree n in X and we have a systematic definition of $T_{i,n}$ which is more satisfactory in this respect than the direct definition of $P_{i,n}$ in terms of X.

The author has usually found it better to divide an interval $a \leqslant x \leqslant b$ into two sub-intervals $a \leqslant x \leqslant \alpha$ and $\alpha \leqslant x \leqslant b$ and use a separate polynomial of degree $n \leqslant 5$ for each such interval rather than to retain the whole interval $a \leqslant x \leqslant b$ and use a polynomial $P_{i,n}$ of degree greater than 5 or a trigonometrical expression like $T_{i,n}$.

ACKNOWLEDGMENTS

Acknowledgment is due to the General Electric Company, Stoke, Coventry, where some of this work was done in 1953; and thanks are due to J. W. Head, Engineering Research Dept., B.B.C., for helpful correspondence. The author also thanks Messrs. Rotol Ltd. for permission to publish this note.

A Simplified Form of the Auxiliary Equation for Use in the Calculation of Turbulent Boundary Layers

by

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(*Cambridge University Engineering Department*)

A NEW type of auxiliary equation is given for calculating the development of the form-parameter H in turbulent boundary layers with adverse pressure gradients. The chief advantage of this new method lies in the rapidity and ease of calculation which has been achieved, without apparent sacrifice of accuracy.

INTRODUCTION

Whereas the growth of momentum thickness in the turbulent boundary layer can now be rapidly calculated by methods involving only simple quadrature[1, 2], the prediction of the form parameter development remains a laborious task, while the results obtained do not always appear to justify the complexity of the calculations.

It was therefore felt worth while to devise a new method for determining the growth of H, concentrating on ease of application, and accepting certain approximations in achieving this.

Of the various parameters which influence the growth of H, the external velocity distribution is by far the most important; this suggests an auxiliary equation in which H is primarily a function of U, with secondary dependence upon θ and R_θ. In order to formulate such an equation, part of an analysis by Spence[3] has been considerably extended to give an integral form of the auxiliary equation.*

NOTATION

x, y co-ordinates parallel and normal to surface

u, v mean velocity components in x, y directions

U free stream velocity at edge of boundary layer

τ, τ_w shear stress, shear stress at wall

$u_\tau = \left(\frac{\tau_w}{\rho}\right)^{\frac{1}{2}}$ friction velocity

$C_f = \frac{\tau_w}{\frac{1}{2}\rho U^2}$ local skin friction coefficient

$\delta^* = \int_0^\delta \left(1 - \frac{U}{u}\right) dy$ displacement thickness of boundary layer

$\theta = \int_0^\delta \frac{u}{U}\left(1 - \frac{U}{u}\right) dy$ momentum thickness of boundary layer

$R_\theta = \frac{\theta U}{\nu}$ Reynolds number based on momentum thickness

$H = \frac{\delta^*}{\theta}$, $\gamma = \left(\frac{u}{U}\right)_{y=\delta}$ form parameters for velocity profile

A, B constants in universal logarithmic velocity profile

k, α constants contained in equation (4)

$n = 2(1-\alpha)\sqrt{(1+k^2)}$

$K = \frac{An}{1-\alpha}$

Z function defined in equation (5)

G function defined in Ref. 5, assumed constant ($= 2{\cdot}8$) in present paper

$S = x_2 - x_1$ length of step in calculation procedure

$\eta = \frac{x - x_1}{x_2 - x_1}$ non-dimensional distance in x-direction

$\beta = \frac{S}{\theta_1 R_{\theta_1}{}^{0{\cdot}402}}$

ϕ function defined in equation (18)

THEORY

Spence[3] obtained an auxiliary equation by formulating the equation of motion,

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = U\frac{dU}{dx} + \frac{1}{\rho}\frac{\partial \tau}{\partial y} \quad . \quad . \quad (1)$$

at height $y = \theta$, with the aid of the continuity equation,

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad . \quad . \quad . \quad . \quad (2)$$

and the equation for the universal logarithmic velocity profile,

$$\frac{u}{u_\tau} = A \log_e \frac{y u_\tau}{\nu} + B. \quad . \quad . \quad (3)$$

*In an unpublished communication Spence has also suggested an integral form of the auxiliary equation, which, however, in general, requires numerical or graphical integration. In the case of a constant negative velocity gradient it reduces to a form similar to that obtained in the present analysis.

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After considerable rearrangement Spence obtained the equation

$$\frac{1}{2\sqrt{(1+k^2)}} \cdot \frac{1}{Z}\frac{dZ}{dx} + (1-\alpha)\frac{1}{U}\frac{dU}{dx} = -\frac{\gamma}{1-2k\gamma-\gamma^2} \cdot \frac{A}{\theta}\left(\frac{u_\tau}{U}\right)^3, \quad . \quad (4)$$

where

$$Z = [\sqrt{(1+k^2)}+(k+\gamma)]^{\sqrt{(1+k^2)}+k} \times \times [\sqrt{(1+k^2)}-(k+\gamma)]^{\sqrt{(1+k^2)}-k}, \quad . \quad (5)$$

$$\gamma = \frac{u}{U}_{y=\theta} \quad . \quad . \quad . \quad (6)$$

and k and α were constants to be determined from experiment.

Equation (4) constitutes the initial equation of the present analysis. To obtain the new auxiliary equation, (4) is integrated to give

$$\log_e \frac{Z_2}{Z_1} + n \cdot \log_e \frac{U_2}{U_1} = -K \cdot \int_{x_1}^{x_2} \frac{\gamma\left(\frac{C_f}{2}\right)^{3/2}}{\theta(1-2k\gamma-\gamma^2)}\,dx, \quad (7)$$

where $$n = 2(1-\alpha)\sqrt{(1+k^2)} \quad . \quad . \quad (8)$$

and $$K = \frac{An}{1-\alpha}. \quad . \quad . \quad . \quad (9)$$

Two equations are now employed to simplify the term on the right-hand side of equation (7).

First, Ludwieg and Tillmann's[4] skin friction law,

$$\frac{C_f}{2} = 0{\cdot}123\,(10)^{-0{\cdot}678H} R_\theta^{-0{\cdot}268}. \quad . \quad (10)$$

and second, Ross and Robertson's[5] approximate expression for the growth of momentum thickness in strong adverse pressure gradients,

$$\frac{\theta}{\theta_1} = \left(\frac{U_1}{U}\right)^{2+G}. \quad . \quad . \quad . \quad . \quad (11)$$

where the subscript 1 refers to some initial point, and G is a function which in general depends upon Reynolds number, but which may be considered constant without great loss in accuracy.

Equations (10) and (11) enable equation (7) to be written in the form,

$$\log_e \frac{Z_2}{Z_1} + n \log_e \frac{U_2}{U_1} = -\frac{0{\cdot}0431\,K}{\theta_1 R_{\theta_1}{}^{0{\cdot}402}} \cdot \int_{x_1}^{x_2} \left\{ \frac{\gamma}{(1-2k\gamma-\gamma^2)} \times \times (10)^{-1{\cdot}017H} \cdot \left(\frac{U}{U_1}\right)^{1{\cdot}402(2+G)-0{\cdot}402} \right\} dx \quad (12)$$

In adverse pressure gradients, to which application of this method is limited, the term on the right-hand side of equation (12) is small compared with either of those on the left-hand side and the following relation is approximately true,

$$\frac{U}{U_1} = \left(\frac{Z_1}{Z}\right)^{\frac{1}{n}} \quad . \quad . \quad . \quad (13)$$

Equation (13) is now used to simplify further the right-hand side of (12), thus

$$\log_e \frac{Z_2}{Z_1} + n \cdot \log_e \frac{U_2}{U_1} = -\frac{0{\cdot}0431\,K}{\theta_1 R_{\theta_1}{}^{0{\cdot}402}} \cdot \int_{x_1}^{x_2} \left\{ \frac{\gamma}{(1-2k\gamma-\gamma^2)} \times \times (10)^{-1{\cdot}017H} \cdot \left(\frac{Z_1}{Z}\right)^{\frac{1{\cdot}402\,(2+G)-0{\cdot}402}{n}} \right\} dx \quad . \quad (14)$$

Inserting the values, $k = 0{\cdot}2$, $\alpha = -0{\cdot}18$, $n = 2{\cdot}4$ as found experimentally by Spence, and $G = 2{\cdot}8$ as suggested by Ross and Robertson, and introducing the non-dimensional distance

$$\eta = \frac{x - x_1}{x_2 - x_1}, \quad . \quad . \quad . \quad (15)$$

equation (14) may be written in the form,

$$\frac{U_2}{U_1} = \left(\frac{Z_1}{Z_2}\right)^{\frac{1}{2{\cdot}4}} e^{-\beta\phi}, \quad . \quad . \quad . \quad . \quad (16)$$

where

$$\beta = \frac{x_2 - x_1}{\theta_1 R_{\theta_1}{}^{0{\cdot}402}} = \frac{S}{\theta_1 R_{\theta_1}{}^{0{\cdot}402}} \quad . \quad . \quad . \quad . \quad . \quad (17)$$

$$\phi = 0{\cdot}0915\,Z_1{}^{2{\cdot}633} \cdot \int_0^{1{\cdot}0} \left\{ \frac{\gamma}{(1-0{\cdot}4\gamma-\gamma^2)} \cdot \frac{(10)^{-1{\cdot}017H}}{Z^{2{\cdot}633}} \right\} d\eta \quad . \quad . \quad . \quad . \quad . \quad . \quad (18)$$

since $\beta\phi$ is normally $<< 1$, (16) may be written

$$\frac{U_2}{U_1} = \left(\frac{Z_1}{Z_2}\right)^{\frac{1}{2{\cdot}4}}(1-\beta\phi). \quad . \quad . \quad (19)$$

γ may now be expressed in terms of H by the empirical relation,

$$\gamma = \left[\frac{H-1}{H(H+1)}\right]^{\frac{1}{2}(H-1)} \quad . \quad . \quad (20)$$

Using this equation together with equation (5), ϕ may be expressed solely in terms of H. Z and γ are plotted against H in Figs. 1 and 2, while in Fig. 3, $\frac{Z_1}{Z_2}^{\frac{1}{2{\cdot}4}}\left(=\frac{U_2/U_1}{1-\beta\phi}\right)$ is plotted as a function of H_1 and H_2. It is now necessary to express the right-hand side of equation (18) in terms of H_1 and H_2, the values of H corresponding to the lower and upper limits of integration.

Equations (5) and (20) show that equation (18) reduces to

$$\phi = 0{\cdot}0915\,Z_1{}^{2{\cdot}633} \int_0^{1{\cdot}0} f(H)\,d\eta. \quad . \quad . \quad (21)$$

The function $f(H)$ is plotted against H in Fig. 4. Now, because of the characteristic variation of H with η in adverse pressure gradients (which may be inferred from Figs. 5 to 7), it would not be unreasonable to expect that a plot of $f(H)$ against η, instead of against H, should tend much more closely to linearity. Investigation of the experimental results considered confirmed this, thereby suggesting the simplification

$$\int_0^{1{\cdot}0} f(H)\,d\eta = \frac{f(H_1)+f(H_2)}{2}. \quad . \quad (22)$$

ϕ can therefore be determined for any values of H_1 and H_2 with the aid of Figs. 1 and 4.

APPLICATION OF THE METHOD

It is assumed that the velocity distribution and the initial value of H are known, and that the development of θ has been calculated independently of H by a method of quadrature such as that of Truckenbrodt[1] or Maskell[2]. Equation (19) can then be solved in the following manner.

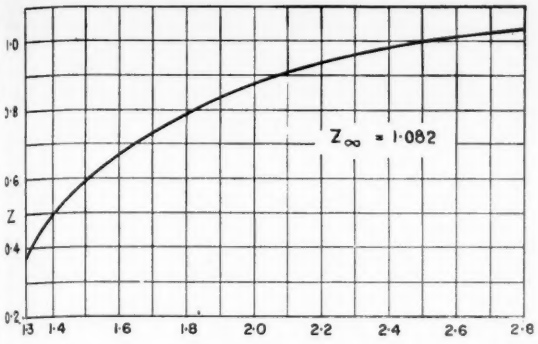

FIGURE 1. Z (equation 5) as a function of H.

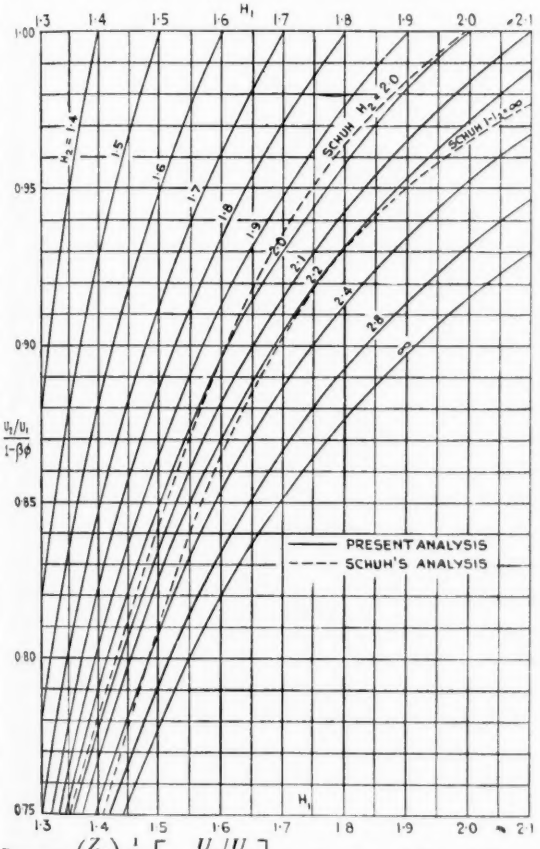

FIGURE 3. $\left(\frac{Z_1}{Z_2}\right)^{\frac{1}{2\cdot4}}\left[=\frac{U_2/U_1}{1-\beta\phi}\right]$ as a function of H_1 and H_2.

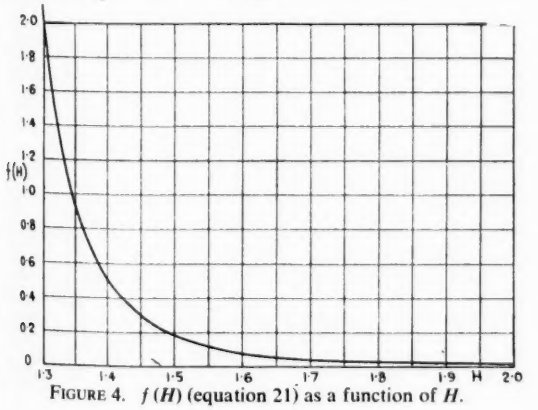

FIGURE 4. $f(H)$ (equation 21) as a function of H.

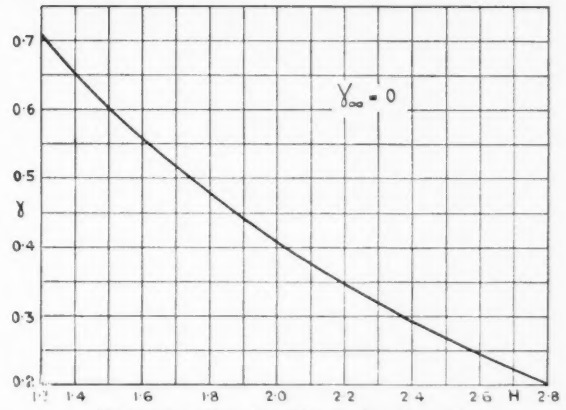

FIGURE 2. γ (equation 20) as a function of H.

Beginning with H_1, the initial value of H, a value of H_2 is selected $=H_1+0{\cdot}1$ (say). From Fig. 3, the corresponding value of $\frac{U_2/U_1}{1-\beta\phi}$ is found, while ϕ is evaluated from Figs. 1 and 4 as described in the previous section. A guess must now be made as to the distance S required for H to increase from H_1 and H_2, and hence a first approximation to β found.

U_2/U_1 is thus obtained and hence x_2 read off from the velocity distribution. The new value of $S(=x_2-x_1)$ is fed back to yield a more accurate value of β, and a second value of x_2 subsequently determined. In general the solution converges rapidly and further iteration should be unnecessary. The procedure is then repeated in step by step fashion from H_2 to H_3 and so on.

It will be found, however, that the value of $\beta\phi$ rapidly becomes negligible after the first few steps. Thereafter any step length may be used without loss in accuracy and the calculation is continued using Fig. 3 only in conjunction with the velocity distribution.

In principle any step length could be used from the beginning of the calculation, but it has been found that more accuracy is obtained by confining the step length to the order of $\Delta H=0{\cdot}1$ until the term $\beta\phi$ becomes negligible.

COMPARISON WITH EXPERIMENTAL RESULTS

The following three sets of experiments have been used to test the accuracy of the present method:—

Author	*Experiment*	*Fig.*
SCHUBAUER and KLEBANOFF[6]	N.B.S. Turbulent Boundary Layer	5
VON DOENHOFF and TETERVIN[7]	Aerofoil N.A.C.A. 65(216)—222 approx. $R=2{\cdot}64\times10^6$, $\alpha=10{\cdot}1°$	6
SANDBORN[8]	N.B.S. Turbulent Boundary Layer	7

In each case the experimental values of momentum thickness have been used in calculating the growth of H by the present method, but this does not invalidate comparison with other methods which have used calculated values of momentum thickness, since the value of θ is of importance only during the initial stages of the present calculation, where any divergence between the experimental and calculated momentum thicknesses must still be small.

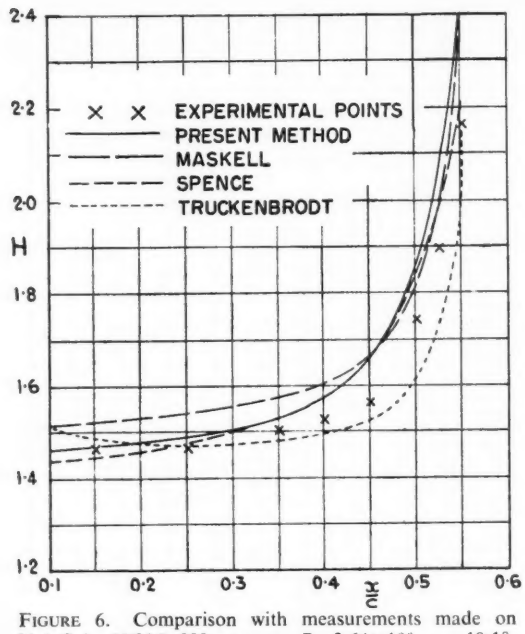

FIGURE 6. Comparison with measurements made on N.A.C.A. 65(216) 222 approx. $R=2{\cdot}64\times10^{6}$. $\alpha=10{\cdot}1°$.

In comparing the results with those of Spence, it should also be borne in mind that, whereas the present analysis involves the Ludwieg-Tillmann skin friction law

$$C_f=0{\cdot}246\ .\ 10^{-0{\cdot}678H}\,R_\theta^{-0{\cdot}268},$$

Spence adopted Squire and Young's[9] law:—

$$C_f=2\,(3{\cdot}59+2{\cdot}56\log_e R_\theta)^{-2}.\quad .\quad .\qquad (24)$$

Where available, curves calculated according to the methods of Maskell[2], Spence[3], Schuh[10] and Truckenbrodt[1] have been included. It will be seen in Figs. 5, 6 and 7, that the present method compares favourably with those of the other investigators.

CONCLUSIONS

From the comparisons given, it may be safely concluded that the simplifications and assumptions introduced in the analysis have been accompanied by no appreciable loss in accuracy, and in view of the primary dependence of H upon the velocity distribution in strong adverse pressure gradients leading to separation, this is perhaps not surprising. It is hoped that the considerable reduction in time and labour which the present method affords may commend it for general application to the prediction of turbulent boundary layer separation.

ACKNOWLEDGMENTS

The author is indebted to Professor W. A. Mair and Dr. M. R. Head for their assistance in the preparation of this note.

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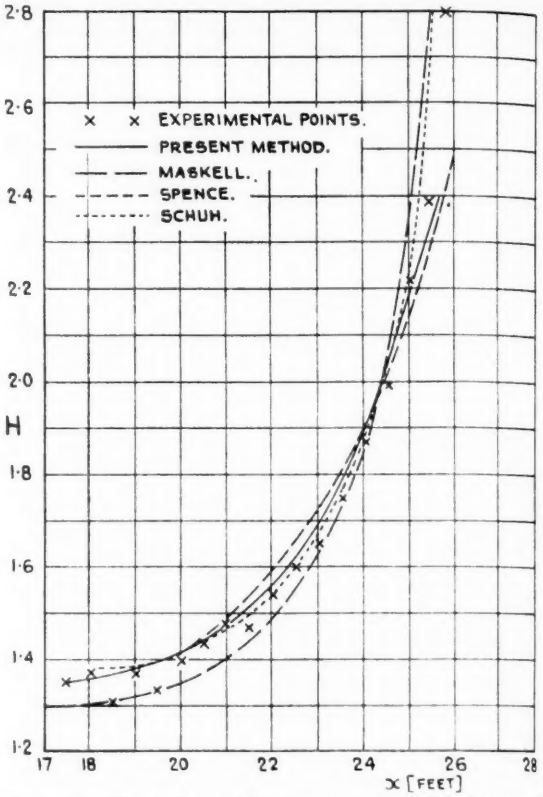

FIGURE 5. Comparison with measurements of Schubauer and Klebanoff[6].

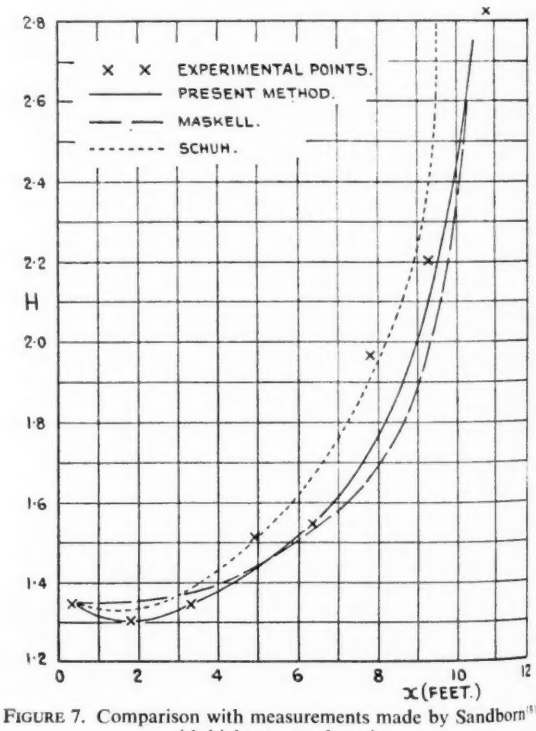

FIGURE 7. Comparison with measurements made by Sandborn[5] with highest rate of suction.

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Note on Matching a Supersonic Intake to an Aircraft Gas Turbine

by

J. M. STEPHENSON

THE FUNCTION of the air intake of a gas turbine engine is to deliver whatever air mass flow is required, with the best recovery of ram stagnation pressure, over the desired range of flight speeds and altitudes.

Although it is generally shown in other forms, the performance of an air intake for supersonic flight can be represented on charts very similar to those of a rotating compressor. In Fig. 1 the ratio between ambient (static) pressure and stagnation pressure at the diffuser of a typical intake is shown as a function of corrected inlet and outlet air mass flow (which are themselves functions of the local flow Mach numbers), for a series of flight Mach numbers. These charts can be compared directly with those for a typical axial-flow compressor (Fig. 2), where stagnation pressure ratio is shown as a function of corrected air mass flow and corrected shaft speed. (The latter is proportional to the Mach number of the tangential blade speed.) The buzz line of the intake, drawn in Fig. 1 at somewhat lower flows than those of the pressure peaks, compares qualitatively with the surge line of the compressor.

Following this general correspondence, it may be seen that the currently important problem of matching an intake to a gas turbine engine compressor, over a wide range of flight Mach numbers, is very similar to the problem which appeared many years earlier, of matching the stages of a high pressure ratio compressor, to ensure stability and efficiency of compression over a wide range of shaft speed and power.

The latter problem was discussed in 1951 by the author[1], when it was pointed out that there are in theory five possible techniques for perfect matching. These solutions are summarised here, with comments on their application to the matching of supersonic intakes to gas turbine compressors. The quotations are from Ref. 1.

(*i*) *Closed-cycle:* "The most simple and specialized solution is to keep the pressure ratio always at the design value . . . altering the inlet density level." This is a common arrangement for closed-cycle gas turbine engines driving constant-speed shafts. Its analogue in the intake problem is always to fly at the same Mach number, power output varying with altitude. This is the solution presently adopted for certain missiles, but is not of general application.

(*ii*) *Variable-pitch compressor blades:* "It is difficult to adjust the rotor blades, but if only the stators are rotated the efficiency can be improved and surging avoided." This technique, with from one to six rows of variable-pitch stators, has since been used on many engines. The analogue for the intake is to vary the angle of the oblique shocks by fore-and-aft movement of a spike or wedge, which is now standard practice on most piloted supersonic aircraft.

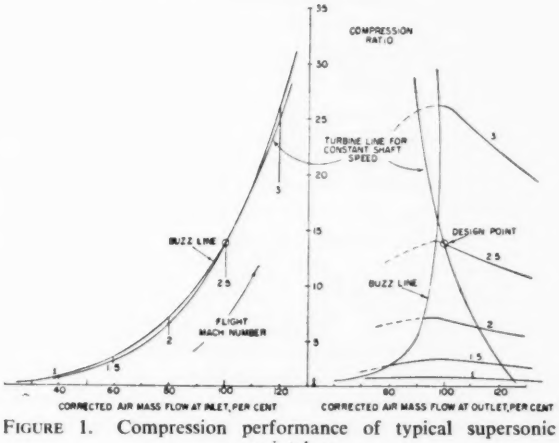
COMPRESSION RATIO
TURBINE LINE FOR CONSTANT SHAFT SPEED
BUZZ LINE
DESIGN POINT
FLIGHT MACH NUMBER
CORRECTED AIR MASS FLOW AT INLET, PER CENT
CORRECTED AIR MASS FLOW AT OUTLET, PER CENT

FIGURE 1. Compression performance of typical supersonic ram intake.

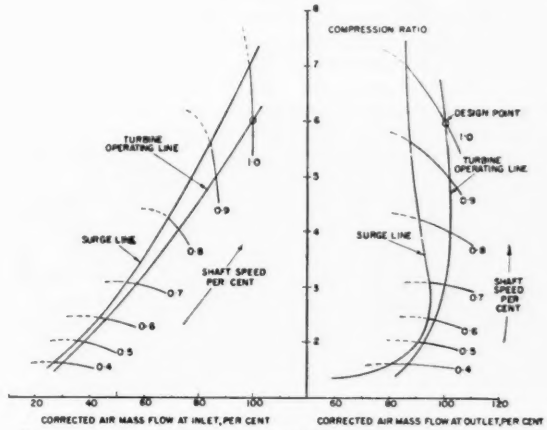
COMPRESSION RATIO
TURBINE OPERATING LINE
SURGE LINE
SHAFT SPEED PER CENT
DESIGN POINT
CORRECTED AIR MASS FLOW AT INLET, PER CENT
CORRECTED AIR MASS FLOW AT OUTLET, PER CENT

FIGURE 2. Performance of typical axial-flow compressor.

Received 11th October 1957.

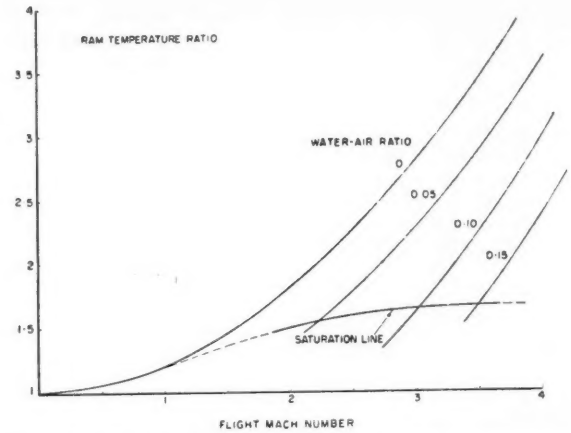

FIGURE 3. Reduction of ram temperature ratio by evaporation of water.

(*iii*) *Blow-off during the compression process:* Blow-off from the intake diffuser is now also standard practice at high flight Mach numbers, where for efficient operation the intake demands a larger air flow than the compressor. "A great deal of power is lost in doing this, so that the efficiency of any plant incorporating such a device is low. Blow-off is only defensible, therefore, for transient conditions in starting compressors." These last remarks must be modified for the case of the intake, for no power is supplied directly, and the drag incurred by passing excess air through the intake and out of the bypass duct may not be much greater than the drag incurred by passing the same quantity of air around the engine nacelle.

(*iv*) *Separate spools:* Dividing the compressor into two or more groups, in which ". . . the rotors are able to turn independently. This arrangement was suggested by Dr. A. A. Griffith in 1929." The two-spool aircraft gas turbine, with its great freedom from surging troubles, is very successful today. The analogue for the intake is to allow the speed of the engine compressor shaft to *rise* as the flight Mach number increases—*i.e.* the exact opposite of what is commonly done today.

The case for controlling an engine so as to hold constant shaft speed (and hence *reduced* corrected speed at high flight Mach number), is that the centrifugal stresses in the rotating assembly are then always at the maximum allowable value, and thus the weight of the rotating parts is a minimum. This argument may lose its force as average flight speeds increase, and the efficiency of the intake at high speeds becomes a more important factor in aircraft performance than the thrust-weight ratio of the engine at take-off.

(*v*) *Variable intercooling:* In Ref. 1 a new matching technique was proposed, which depended on varying the polytropic exponent of the compression process by extracting heat, as follows: "The solution put forward here, and which is in theory most promising for many applications, is . . . variable cooling of the gas during compression. . . . A device to effect this was patented by the author and Power Jets Ltd. in July 1948[2]." In land and marine gas turbine engines with exhaust heat exchangers, where cooling within the compressor is often applied anyhow to improve the thermal efficiency, it is easy to vary the degree of cooling to ensure matching. Indirect cooling has not been thought very practical in aircraft gas turbines, to date; but the possibility exists of cooling the air during compression by injecting liquid directly into the airstream so that it evaporates, as has been done for the superchargers of high-power piston engines.

Following again the analogy with the intake, liquid can be injected between the diffuser and the compressor entry. The degree of cooling obtained at any given flight speed and altitude can be calculated from psychrometric tables. But a simple approximation is obtained by assuming that each one per cent of water-air ratio by weight reduces the ram temperature ratio by 0·12, so long as the air is not saturated. The resulting ram temperature ratio is shown in Fig. 3 as a function of flight Mach number and water-air ratio.

Note that the sense of cooling appears at first sight to be opposite from that of the intercooled compressor. In the latter, the air within the compressor is cooled more strongly at shaft speeds *below* the design value, because the front end of the compressor cannot slow down relative to the high-pressure end. In the present case of matching an intake with a compressor, the air is cooled at flight speeds *higher* than the design value, because the compressor at the high end of the compression process is not allowed to speed up.

The use of cooling by water injection has a further attraction in aircraft gas turbines, in that it increases the power available from a given size of engine. Thrust augmentation by water injection into the combustion chamber of a turbo-jet engine is, of course, well established in service, where it is chiefly used to reduce take-off run of underpowered aircraft. One of the most comprehensive discussions of thrust augmentation by liquid-cooling was given in 1951[3].

The purpose of this note is to point out that the possible techniques of matching a supersonic intake with the compressor of a gas turbine engine are closely analogous with the known solutions of matching the high and low pressure ends of a mechanical compressor. In particular, the combination of substantial thrust boosting with exact matching over a wide range of flight Mach numbers may make liquid-cooling an attractive solution.

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News from the Divisions

It has been suggested to the Divisions of the Society overseas and to the Singapore Branch that, instead of publishing their Annual Reports, it would be of more general interest to publish, two or three times a year, news of their activities and of aeronautical developments in their areas. This month we publish reports from the New Zealand and Southern Africa Divisions and hope that we shall have news soon from the Australian Division and the Singapore Branch.—Ed.

From New Zealand

T. T. N. COLERIDGE, A.F.R.Ae.S., Honorary Secretary

The New Zealand Division's activities have continued during the past year on the same general lines as previous years and no particularly outstanding developments call for remarks. We are, however, very pleased to see that the Palmerston North Branch, after some years in recess, has started up again and a number of meetings, well supported, have been held. This particular Branch is in the centre of one of the most active areas for aerial top dressing and other agricultural activities. There are a number of the aviation agricultural concerns in the vicinity and it is hoped that a Branch here will be the means of fostering the interests of the Society in this area.

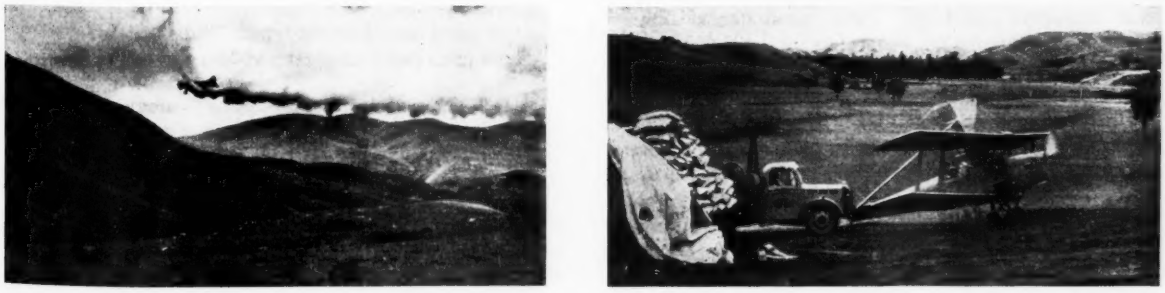
Aviation agricultural activities continue to expand steadily. The growth of this particular Branch of the Industry is not so spectacular as it was some years back, but it is now firmly established and is now an important factor in the general productivity of the country. The latest statistics show that in twelve months a million individual flights have been made on Aerial agricultural operations and over four million acres have been treated.

It is with great regret that we have to record the death in an aircraft accident of Mr. T. O'Connell, the General Manager and the moving spirit of Straits Air Freight Express. The freight-carrying activities of S.A.F.E. between the North and South Islands of New Zealand have introduced new ideas in aerial freight operations. The short haul (about 70 miles) on which the backbone of this service rests has been made economically successful by cutting to a minimum the aircraft idle time on the ground. It is here that Mr. O'Connell and his staff have really led the way with their own specially developed cargo system of packing, loading and unloading so that the aircraft utilisation has been pushed up to an extent which is a source of amazement to all overseas visitors. Mr. O'Connell's death is a very great loss indeed to New Zealand and to Aviation generally.

In the past twelve or eighteen months New Zealand National Airways Corporation have been preparing for their change over to Vickers Viscounts next year. New Zealand, with the advent of the Viscount, will definitely now be taking the first step into the turbine-engined aircraft age and, just as it has been with other countries, major changes in ideas are involved as well as mere changes of equipment. The meticulous attention being given to the multitudinous details of the change-over has demonstrated clearly that the revolutionary nature of the change is fully appreciated.

One major project now progressing rapidly is the aerodrome extension in Wellington City. The mountainous country extending all round Wellington for something like 50 miles in every direction has made the problem of aerodrome siting as difficult as this problem is likely to be.

The problem of no flat country has been overcome in the only possible way, namely, by literally digging away one hill and putting it into the sea. The resultant aerodrome can never be of fully international standard but will have the great advantage of being within a quarter of an hour's run of the very centre of the city. Being capable of handling Viscounts the most important need will be met. The question of the extent of its further usefulness is, and no doubt will continue to be for some time, a very fruitful cause of heated and technical arguments. For difficult problems such as this there will always be violent disagreement with the



Typical photographs of aerial spraying activities in New Zealand. On the left a D.H. Beaver and right, a specially modified D.H. Tiger Moth being re-loaded.

solutions adopted, but the aviation industry has reason to be grateful for the vision and courage of those who have made the decision. When completed, it seems to us that Rongotai Airport will be able to claim that it is unique in at least one way. It will be the only aerodrome we know built in a wind tunnel!

From Southern Africa

Mrs. D. D. HUGHES, *Companion*, Honorary Secretary

In order to create interest, particularly among aeronautical personalities in the Union and in Southern Africa generally in the Division's activities, it was decided to hold a cocktail party in the Langham Hotel, Johannesburg, on the 6th March 1957. This, with an attendance of over 90, among whom were many prominent aeronautical personalities in the Southern Africa area, including some as far afield as Salisbury and adjacent northern territories, was a great success. The toast to the Society was proposed by Dr. A. J. A. Roux, Director of the National Physical Laboratory, Pretoria, and the reply was given by Professor W. J. Walker.

During the year several very interesting and well attended lecture meetings were held in Johannesburg and elsewhere, among which were the following: —

"Safety Design Aspects of the Boeing 707" given by Mr. Fitz-Simons, a representative of the Boeing Airplane Company, on the 15th May. At the same meeting a film entitled "Over the Pole," kindly lent by the Scandinavian Air Lines System (S.A.) Ltd., was also shown.

On 26th June, Dr. E. A. Bunt, A.F.R.Ae.S., delivered a very informative lecture, illustrated by films, on "The Development of Guided Missiles." This lecture was also given later at Durban and Salisbury to members of the Division.

On 21st August, Mr. John Nash, A.F.R.Ae.S., gave a much appreciated lecture, with film illustrations, on "Supersonic Aircraft." This lecture is likely to be given also at Durban and Salisbury.

The concluding lecture of the year was given by Mr. H. A. Simon, A.F.R.Ae.S., on the 5th December, entitled "The Theory of Helicopter Flight."

Seventeen new members of the Division have been elected during the year.

An interesting development which has found a final and very practical issue is contained in the recent result of the Division's endeavours to secure Union Departmental recognition of the Society's examination and fellowship qualifications. After considerable correspondence had been conducted and interviews arranged and held, a letter was received on 1st June last from the General Manager of the South African Railways, under whose administration the South African Airways is included, informing the Division that—"servants of this Administration employed in the South African Airways Department who are Associate Fellows of the Royal Aeronautical Society and whose membership was achieved by examination, will in future be eligible for appointment to engineering positions in the South African Airways Department provided they comply with certain departmental requirements."

In this connection it should be mentioned that correspondence is now in progress with the Minister of Education, Arts and Science, whereby it is hoped to arrange for the reciprocal recognition of the examinations of the Society and those of the Department of Education, Arts and Science.

The Division very much regrets to announce the death towards the end of the year of its Honorary Vice-President, the Honourable J. H. Viljoen, Minister of Education, Arts and Science.

At present we are busy pursuing the question of the recognition of the Society's Qualifications with the Rhodesian Federation and the East African Government.

Graduates' and Students' Section

VISITS

Vickers-Armstrongs (Aircraft) Ltd.

On 11th January we visited Vickers-Armstrongs (Aircraft) Ltd. at Weybridge. The Section has visited Vickers several times previously, at three or four year intervals, and each time they have had a new aeroplane type to show us. This time the aeroplane was the Vanguard, preparation for the production of which was well under way, although the prototype-cum-first production aircraft has not yet flown.

We saw the Vanguard mock-up, which occupies a separate building, and consists of the usual fuselage, and a half wing as well, right to the tip. One has to see this to appreciate what a large aeroplane it is, not just a little bigger than a Viscount, but more the size of a Stratocruiser.

In the workshops, one noted the extensive use of fibre glass jigs for smaller components and assemblies. These are quicker and cheaper to make than welded steel ones. The Vanguard fuselage is assembled from segmental prefabricated panels, which seems to be the vogue nowadays, but although the design appeared to be quite orthodox, it was also apparent that much thought had been devoted to details.

The Vanguard fuselage was being built at one end of the assembly lines, while at the other end there were quite a few Viscount 800 series, production of which is going "full blast."

Guinness Brewery

The Guinness Brewery at Park Royal is a brewery with a difference. When we visited it on 1st February we were assured, and could believe, that it is the biggest, most modern and cleanest brewery in the country, but still only about a third of the size of their old brewery in Dublin! They employ comparatively few people, despite their days being punctuated by lunch, tea and beer breaks. This is because mechanical handling is used to the full. The brewery is never shut down, operating day and night every day of the year. In the vat house, where Guinness is stored for a day or so, they were replacing the original wooden vats by stainless steel ones, welded up on the site in half inch thick plate. Each vat holds 10^7 glasses of Guinness or thereabouts. At the dispatch end there was an impressive fleet of 3,000 gallon road tankers. It seems that H.M. Customs and Excise collect duty at a sufficient rate from Park Royal's output to buy a V-bomber and a half each week.

Forthcoming Visits

A visit has been arranged to the B.O.A.C. Engineering Base, London Airport, on 31st May 1958. Further details will be announced later.

Honorary Treasurer

You may have wondered just what the duties of this high sounding office entail. Perhaps you picture the treasurer sitting up to the small hours counting the subscriptions of the impecunious Graduates and Students and considering how they can be spent.

Unfortunately nothing is further from the truth. The sole income of the Section is £25, an annual grant from the main Society.

The way this came about was that the Section had run one or two social events which, due to lack of support, were rather disastrous financial failures. The Secretary said this must stop and he would arrange to give us a grant from which we must meet all our expenses, and when this was gone the committee must meet the rest themselves. Consequently the finances of the Section have been on a firmer foundation since then.

The sort of expenses we do have are postages of all the various Section Officers, losses on coaches hired for visits, hire of films and last, and greatest, subsidising the Annual Section Dance in the autumn. We have budgeted for a loss on our Summer Parties, but due to the valiant work of our lady friends in preparing sandwiches and so on, have managed to make a small profit.

Mr. Treasurer has quite a tricky job to stretch the £25 throughout the year and yet prevent the committee having to dip into their own pockets. W.E.C.

Annual General Meeting

The Annual General Meeting of the Graduates' and Students' Section will be held in the offices of the Society at 4 Hamilton Place, W.1, on Tuesday 25th March 1958 at 7.30 p.m. Light refreshments will be served from 7.00 to 7.30 p.m.

AGENDA

1. To consider and approve the minutes of the previous Annual General Meeting.
2. To consider any business arising from these Minutes.
3. To receive the report of the Committee on the activities of the Committee and Section during the past year.
4. To make representations to Council on the names of the representatives of the Section to serve on the Committee for the year 1958-9.
5. To discuss the future activities of the Section.
6. To consider any other matters connected with the affairs of the Section.

Nominations for the Section representatives on the Committee for the year 1958-9 are invited, and should be sent to the Hon. Secretary: Mr. P. D. Stewart, 10 Abbey Gardens, Chertsey, Surrey.

All nominations must be both proposed and seconded, with the candidate's agreement, and all concerned must be Graduates or Students. The number of vacancies to be filled is nine, and if the nominations exceed this number a ballot will be held during the meeting. The names of the successful candidates will be subject to confirmation by Council.

Members are reminded that it is desirable for the Committee to be representative of as many firms and colleges as possible.

The meeting will be followed by a film show:—
Mickey Mouse cartoon: The Plastics Inventor.
Part I of High Speed Flight by the Shell Film Unit and either Part II or Guided Weapons films.

THE LIBRARY

Reviews

THERMAL POWER FROM NUCLEAR REACTORS. *A. Stanley Thompson and Oliver E. Rodgers. Chapman & Hall, London, 1956. 229 pp. Illustrated. 58s.*

This is a book on nuclear reactors written for engineers and is based, in part, on a series of lectures given by one of the authors at the Oak Ridge National Laboratory in 1952. The first half is devoted to nuclear considerations such as the fission process, criticality and reactor kinetics. The explanations are clear and easy to follow though there is insufficient detail to enable the reader to undertake quantitative work without reference to other books. The second half of the book deals with the engineering aspects, including heat transfer where the treatment is concise and clear, and reactor materials where it is essentially qualitative.

In the first chapter the authors deal with the structure of atoms, radioactive emanations and the various interactions between neutrons and nuclei. The fission of uranium and breeding conversion are briefly described.

The next two chapters are devoted to calculations of neutron distribution, criticality and reactor kinetics. Emphasis is placed on the usefulness of simple diffusion theory with corrections based on transport theory. The limitations of this method of calculation are explained. Analytical solutions to the diffusion equation for fast reactors and idealised thermal reactors are explained in some detail and a method of tackling more complicated reactors which require numerical solution is given.

The transient behaviour of reactors is approached by discussing those features which are peculiar and non-linear. There are good explanations of xenon poisoning and temperature coefficient of reactivity followed by the derivation of the reactor kinetic equations. The subject of reactor control is dismissed in one page as being too complex for analytical computation.

Chapter 4, on radiation shielding, gives a good introduction to the problems involved without going into enough detail to allow the reader to solve any of them. Chapter 5 similarly gives an idea of the properties required in reactor materials and the damage caused by irradiation. The latter is clearly explained with reference to work hardening in metals.

Thermal stress in fuel elements is explained in some detail in Chapter 6. Equations for various configurations are presented, but the explanations of the equations are not so good as the general "order of magnitude" description in the first few pages.

The chapter on power extraction from reactors gives a good summary of the relevant heat transfer equations for forced convection and boiling heat transfer. The phenomenon of burn-out is briefly mentioned, but no method of calculating this is given.

The last chapter deals with thermal power cycles. The authors have not been able to do justice to this somewhat complicated subject, and since it is well covered in the literature this chapter could have been omitted with little loss of completeness.

This book is certainly a good introduction to the novel problems associated with nuclear engineering. It would be most helpful to an engineer commencing this type of work.—JOHN S. HOLLINGS.

JANE'S ALL THE WORLD'S AIRCRAFT, 1957-1958. *Compiled and Edited by Leonard Bridgman. Sampson Low, Marston & Co., London, 1957. 488 pp. Illustrated. 5 gns.*

There cannot be many people with the slightest interest in aviation who have not seen copies of "Jane's" on library shelves at some time in their experience and, yet, how many of them take it for granted as a reference book of aeroplanes? If, like the reviewer, they sat down and studied one of these beautifully produced volumes, they would find that it contains far more of interest than they had realised. That is one of the troubles with an annual of this sort—so much has to be carried forward from year to year and the publisher has to face the fact that, despite his efforts to introduce new material, so often the result is written off as the latest edition of so-and-so.

"Jane's" is now forty-eight years old and every year the most impressive thing about the book is the quantity of new material, particularly photographs, which appear in it—often hitherto unpublished. The latest volume is no exception.

The years preceding 1952 were covered in a rather different way from the present layout. Quite a lot of space used to be devoted to historical and political aspects of aviation in the countries under review and military and civil aircraft were each given a separate section. The military section has now been dropped and the civil section has been condensed into a tabulated record of traffic figures for 297 of the world's scheduled airlines. This is a rather inadequate substitute but, perhaps, more in keeping with the title of the book.

The main section dealing with aeroplanes covers 339 pages which include no less than 761 illustrations, of which 434 are new. The quality of the half tones is, as usual, excellent in nearly all cases—the only exception being illustrations of certain foreign aircraft of which photographs are difficult to obtain. In the engine section, of 94 pages, no less than 61 are devoted to turbines and to rockets. There are a large number of illustrations, a third of which are new. Altogether no less than 590 illustrations in this volume are different from those which appeared last year and contribute much to the up-to-date appearance of the book.

There is a small section, tucked away between aeroplanes and engines, for guided missiles and for missile test vehicles; this is not a really satisfactory solution to a rapidly growing problem and before long it will be necessary to provide a full coverage instead of tabulated details of missiles, supplemented by further details under manufacturers in the aeroplane section. It is rather a muddle, as might be expected at a time when the aircraft industry is undergoing such a vast evolutionary upheaval.

The index now appears in the front of the book and there is a separate section for rotary wing aircraft which is quite a useful idea. Guided missiles could do with one too, but perhaps that will come later.

"Jane's" can never be really up to date but Leonard Bridgman and his newly acquired Assistant, John W. R. Taylor, come very close to achieving the impossible. In every respect the new "Jane's" is a worthy edition of a rightly famous book.—A.S.C.I.

HIGH-SPEED AERODYNAMICS (COMPRESSIBLE FLOW). *Elie Carafoli. Editura Tehnica, Bucharest, 1956. 710 pp. Illustrated.*

The author is head of the Institute of Applied Mechanics at Bucharest, and has made a number of individual contributions to compressible flow theory, and written an earlier book on low-speed aerodynamics. The present book was originally published in Rumanian, but the English of the translation is, on the whole, excellent; the notation differs in some respects from that used in this country, but this should not inconvenience the reader unduly. The book is well produced and printed, and the price is low compared with that of volumes of comparable size published in this country.

The book deals mainly with the theory of inviscid compressible flows, the treatment is detailed, and little previous knowledge of aerodynamics is assumed. The early chapters discuss basic mathematical and thermodynamical concepts and the various forms of the equations of motion. The subsonic and transonic flows past aerofoils, bodies and wings are then considered, and chapters on approximate and exact solutions for supersonic flow follow. There is then a detailed account (occupying about one quarter of the book) of linearised solutions for the supersonic flow past wings of finite span and, finally, a brief account of unsteady flows. There is no discussion of the theory of hypersonic flow, and no direct discussion of transonic similarity theories.

There is little account of experimental methods and, judging by the examples that are included, the author is not familiar with many recent experimental results. Boundary layer and other viscous effects are not described in any detail, except in the description of the effects resulting from the interaction between shock waves and boundary layers in the transonic flow past aerofoils. The account is not up to date and is, in places misleading.

Although there is a detailed list of contents, no index is included, and this omission detracts from the value of the book for reference purposes. Also, a comparatively small number of references are made to original papers or other text books on the subject.

In view of these shortcomings, the book cannot be regarded as a good general text book on high-speed aerodynamics, although, if the shortcomings are appreciated, it can be recommended as a useful account of the theory of inviscid compressible flow.—D. W. HOLDER.

THE SOURCES ON INVENTION. *John Jewkes, David Sawers, Richard Stillerman. MacMillan & Co., London, 1958. 428 pp. 31s. 6d.*

This is an important book.

It is critically concerned with problems arising out of the apparent increasing pace of technological endeavour, coupled with the decreasing freedom of scientific purpose and individual thought. This book is opportunely published at the time when there is much uneasiness and speculation about the future of mankind in a world of amoral science and mass minded technology.

The authors draw their conclusions and speculations from case histories of world-wide successful inventions in many fields; from the experiences and conclusions of individuals; from the methods of monopolistic industrial corporations; and from institutions, government and educational and private, in the fields of research. The book is written with an intelligent provocation which yet calls for serious consideration by economists, industrialists, scientists, technologists, optimists and pessimists.

Of technical *progress*, "We must go faster to stay where we are; if, in the future, for example, ways are invented of making a jet engine quiet, then the skies will merely be as silent as they were before the invention of the jet engine." An interesting thought!

Of scientific endeavour, "It is not inevitable that the country with the outstanding scientific successes will be the richest country."

"The development of the bomb would seem to have no lessons to teach us about the best ways of exploiting new ideas for peace time purposes. *It was magnificent, but it was not economics.*" (Reviewer's italics.)

The authors have the turn of phrase which is remembered. Discussing the danger to the autonomy of science and technology in the Universities, they write, "It is much to be hoped that scientists and university administrations will recognise and resist the encroachments of outside bodies, and the lure of tempting grants which turn the Universities into *tied houses.*" (Reviewer's italics.)

It is precisely because this has happened in so many American Universities that there has been such an outcry about scientific education on fundamental matters in the United States. American Universities are usually teetotal!

Evidence is set forth by the authors which heavily weighs down the scales in favour of the individual inventor. "If invention ever became the prerogative of full time professional employees there are grounds for believing it would be weakened in range, liveliness and fertility."

The authors, indeed, appear to conclude that the arguments for monopoly in any form, are not very good arguments either in research, invention, size, or economics. It is, I believe, more than likely that mass production methods produce mass brain-washing machine minds, with the lowest common denominator.

This book is well written, well documented, and well worth reading by all who believe in the ultimate dignity of man and who wish to have some understanding and evidence of the fundamental truth "More haste less speed," whether in science, technology or human relationships.

The University of Chicago has sponsored this investigation of an almost unsurveyed field, and is to be congratulated, with the authors, upon the result.—J. LAURENCE PRITCHARD.

SUBCONTRACTING POLICY IN THE AIRFRAME INDUSTRY. *John S. Day. Harvard University, Boston, 1957. 327 pp. 32s.* and

MANAGEMENT CONTROL IN AIRFRAME SUBCONTRACTING. *Neil E. Harlan. Harvard University, Boston, 1956. 256 pp. 32s.*

Both published by the Division of Research—Graduate School of Business Administration, Harvard University, Boston, U.S.A. British Agents: Bailey Bros. & Swinfen.

These two books—each about 300 octavo pages—are companion volumes dealing with the study which the authors have made of the problems, practices and the methods actually used by the American Aircraft Industry in placing and controlling sub-contracts.

Professor Day's book deals with the basic reasons for placing sub-contracts and examines the economic aspects—the legal problems and method of formulating policy for permanent or temporary sub-contracting. He also examines the problems of selecting the items to be sub-contracted and the choice of a firm to do the work. The effects of Government procurement policy and the methods of payment are also examined.

Professor Harlan's book concentrates on an examination of the ways in which "prime" contractors did in fact exercise control over the basic factors of delivery times,

quality and cost. The first part largely concerns itself with the creation of conditions under which effective control can be expected—including the various levels at which such control must be initiated and exercised; including getting the "house in order" at the main firm.

Then the problems of quality and delivery are considered and finally the complex relationship of cost control and the interaction of engineering modifications and delivery variations are dealt with.

Professor Harlan's book is probably of the greater practical use to British aircraft firms, as the technical aspects in both countries are obviously more similar than are the legal and commercial relationships. Both studies —as is typical of the Harvard Business School approach— contain a large number of detailed "case studies." From these it is possible to understand clearly the problems which have to be envisaged in the conducts of complicated negotiations each as placing aircraft sub-contracts geared to a main contractors programme.

Both books taken separately are extremely well written and presented, though one might feel that they could be condensed into one volume not much larger than either. There is, in fact, no serious duplication. There is merely a rather excessive examination of detail which is in essence fairly obvious and which leads to some conclusions common to both studies. As separate books this degree of redundancy is probably unavoidable.

One of the interesting aspects of the books is the disclosure of the close similarity of the philosophy held and of the problems experienced in the aircraft industry of the United States and this country. Nothing but benefit could come from a close study of both by manufacturing executives in all industries which are concerned with sub-contracting any part of their programme. The aircraft industry can hardly afford to overlook this unique study of one of its major problems.—J. V. CONNOLLY.

L'AVIATION NOUVELLE. *Camille Rougeron (Editor). Larousse, Paris, 1957. 447 pp. Illustrated. (In French.)*

This book aims at giving an account, not of modern aviation as a whole (although it is in fact pretty thorough), but at least of its major aspects and its most important recent developments. It is nominally addressed to the layman, but the authors do not talk down to him on technical issues; these are explained in fairly simple language, yet on a level high enough to prevent boredom in the technical reader. Fundamentals of flight are omitted, to keep the work within bounds. The editor is personally responsible for eight of the chapters, and other eminent authorities (including Maurice Roy) have contributed.

The first chapter (by M. Rougeron) is of outstanding interest, and expounds the author's philosophy on development policy. Lord Fisher's dictum, "The scheme, only the scheme," is his theme. Problems of technical execution can always be solved nowadays, he argues, if necessary by catching up on mistakes during the development period, and even some crudities can be tolerated if the specification is right (the Mig 15 is cited as an example). The fatal mistake is to seek "the golden mean"; success is assured only to him who exploits any new advance (such as jet propulsion) to the extreme of its possibilities. Thus the DC-4 was, in its time, the extreme in size and speed compatible with an unpressurised cabin, and within that specification can hardly be bettered today. The Avro Canada "Jetliner" and the "Comet" are held up as examples of the "golden mean" approach; they did represent a substantial progress, but their appeal was limited by the threat of competition of still more economical aircraft, which materialised as the Boeing 707 and DC-8, which are considered to be extreme realisations, as regards size and speed, within the general specification of subsonic jet transports. To exploit possibilities to the extreme, there are prices to be paid (higher weights, higher landing speeds, longer runways), and it is contended that these prices are always worth paying.

This thesis is pursued into the military field. The Mach 2 "Starfighter" (remarkable as it is) will soon be outdated, because the present practicable extreme for supersonic fighters is, M. Rougeron believes, about 1,800 m.p.h. He also contends that, provided the policy of extremes is pursued, highly specialised single-purpose aircraft are unnecessary; the really efficient aeroplane eventually turns out to be suitable for a whole range of duties, indeed sometimes for almost everything except its originally intended role.

The reader is then given a brief glimpse of aeronautical research and hypersonic techniques. There follows an excellent chapter entitled "The airframe and its shapes," which gives a very lucid account of present-day design problems, including the pros and cons of wing shapes current today, and problems arising from the various forms of propulsion. The next two chapters deal with civil and military aircraft, with tabulated data on current types.

The following chapter, dealing with rotary wing aircraft and their applications, is everything it ought to be, with very clear explanations of the various forms of rotor drive, and a brief discussion of convertiplanes and other hybrid types. There is an adequate chapter on turbine engines (with, however, only brief mention of turbo-props), and a briefer one on rocket propulsion—ram-jets and pulse-jets are mentioned only in passing. The next chapter, on modern manufacturing methods, is extremely well-informed, and deals, in passing, with the structural problems of high-speed aircraft, which are not covered elsewhere. Part 1 concludes with a chapter on aviation medicine.

Part 2 of the book is devoted to air transport. There is a chapter on airports, with a brief discussion of layout problems, and an account of the organisation of Paris and New York airports; on "the meteorological protection of high altitude flight," including information on jet streams, but none on clear air turbulence (this is briefly referred to in the chapter on gliding); on radio aids to navigation, including approach aids and collision warning; on air routes, airline companies, and passengers and freight. The author of these last three chapters (Dr. Serraz) has obviously been at some pains to give his readers worthwhile information without wearying them with a wealth of statistics, and succeeds in providing good—and sometimes entertaining—reading; there is an excellent passage on competition, in which Dr. Serraz argues that past attempts at unifying European air transport have been (and future ones on the same lines will be) doomed to failure because European services are in effect feeder lines for the long-range routes where the real profit lies, and it is useless to try to integrate the former without touching the latter. French companies are dealt with in some detail, and the account of the struggle between the Independents and Air France is quite absorbing.

Part 3 is entitled "Aerial Work." Chapters deal with aerial photography; aviation as an aid to geography; postal services; surveillance missions (iceberg patrols, control of insects and other pests, fire and flood fighting, care of herds, power line maintenance, and air police); and finally gliding. Technical problems are discussed where necessary, but the main emphasis is on describing the benefits brought by aviation in the fields concerned, and this the authors do

with becoming enthusiasm. The chapter on postal services contains some account of French pioneering work in this field; postal services were set up in 1918 by Pierre Latécoère and Didier Daurat. Daurat "imposed on his pilots a higher degree of discipline than any military commander would have dared. . . . He imbued them with that cult of punctuality which is still the religion of night mail services today. It is under this impulse that one night Guillaumet arrived at a ranch in the Andes, exhausted by five days' march through the snow, having left his shattered aircraft and lost all his equipment, but still carrying the mailbag . . ."

Part 4 is devoted to military aviation; atomic and hydrogen bombs are discussed in some detail; there follows some material on missiles, which is rather disappointing, and fails to give a really good account of the various guidance methods, or extensive data on current weapons, such as is available for instance in a recent issue of *Flight*. The chapter on air defence is better; radar—not shunning technicalities—takes pride of place, followed by operations control and other aspects of defence. The next chapter "Tactical Missions," gives a most interesting account of the "triumph" of tactical air support in the hands of the Allies in the Second World War, its initial success in Korea, and its final defeat by the effective counter-measures of the Chinese—North Korean command, and likewise in Indochina. The three following chapters deal with strategic missions, naval aviation, and military air transport.

The book ends with a chapter entitled "The Future of Aviation." Here are discussed supersonic flight and the thermal barrier, direct-lift, V.T.O.L. and S.T.O.L. aircraft (all too briefly, alas), jet flaps, and ballistic missiles.

The book is profusely illustrated with excellent diagrams and photographs, both black-and-white and coloured, and beautiful engravings at the chapter headings.

The exceptionally high standard maintained almost uniformly throughout the book by its nineteen different authors represents a remarkable achievement. Practically all significant developments publicly known up to about the end of 1956 are covered, including even such items as results of recent American manoeuvres, and the authors appear to be about as well acquainted with developments in foreign countries as with those in their own. It would be almost dreary if different authors did not occasionally contradict one another on matters of judgment or opinion ("the allied strategic bombing offensive against Germany was, on the whole, a failure," says one; "it was a success," says another), and a slight amount of overlap between some of the chapters is hardly a subject for criticism.

The layman seeking an accurate and comprehensive picture of modern aviation will certainly find it in this book, while even the specialist in one branch or another of aviation may well obtain from it some enlightenment on branches beyond his detailed knowledge, or at the least read it with pleasure.—R. HADEKEL.

Additions to the Library

Aerodynamics. T. Nonweiler *et al.* Series of papers reprinted from "Research." Vol. 10. Butterworths. 1957. 47 pp. Illustrated. 7s. 6d. The titles are:—Aerodynamics, T. Nonweiler; Wings and Bodies in Low Speed Flow, J. L. Stollery; Aircraft Performance, Stability and Control; High Speed Flight, J. Black; The Aerodynamic Laboratory, J. Black; Current Aerodynamic Problems, W. J. Rainbird.

Apron Requirements for Turbine-Powered Aircraft. I.A.T.A., Montreal. 1958. 57 pp. 75 cts. A supplement to the "Airport Buildings and Aprons" Reference Document published by I.A.T.A. in July 1956, which dealt primarily with piston-engined aircraft. Compiled by a group of specialists on technical, operations, cargo and passenger traffic and facilitation matters, it covers general considerations of blast, heat, fumes, noise and fuel spillage; also apron systems and requirements, fixed servicing installations and apron load handling facilities.

Automation in North America. Dept. of Scientific and Industrial Research. Overseas Technical Reports No. 3. H.M.S.O., London. 1958. 66 pp. 4s. A reprint of visits by S. B. Bailey to industrial, commercial and research establishments in the United States of America and Canada made during the winter of 1955-56. There is a special section on aircraft and aircraft engines and among 40 or so organisations visited altogether are Convair, Douglas Orenda Engines, and the N.A.C.A. Lewis Flight Propulsion Laboratory.

Definition and Significance of the Flow Coefficient in Accelerated Flow, with Special Reference to Metering Devices. T. H. Redding, B.S.I.R.A. Research Report M30. 1957. 30 pp. 5s. 6d.

Evidence in Camera. C. Babington Smith. Chatto and Windus. 1958. 252 pp. Illustrated. 18s. *To be reviewed.*

Fluid Pressure Mechanisms. Second edition. H. G. Conway. Pitman and Sons, London. 1958. 231 pp. Illustrated. 32s. 6d. The previous edition was published in 1949. This second edition takes in the considerable developments since then in the manufacture and use of light-weight precision industrial hydraulics. Additions include a substantial revision of the chapter on servo systems.

Ford Story, The. W. T. Larkins. Robert R. Longo Co. Kansas. (In England W. E. Hersant.) 1957. 178 pp. Illustrated. 35s. A Pictorial History of the Ford Tri-Motor.

Gee Bee Story, The. C. G. Mandrake. Robert R. Longo Co., Kansas. (In England W. E. Hersant.) 1957. 106 pp. Illustrated. 17s. 6d. The story of the rise and fall of the Gee Bee organisation, of their aeroplanes and of the great contribution to aviation made by the Granville Brothers.

History of the U.S. Air Force, A, 1907-1957. Alfred Goldberg (*Editor*). D. Van Nostrand, New Jersey. 1958. 277 pp. Illustrated. 51s. *To be reviewed.*

Modern Technological Education for Industry. North Gloucestershire Industrial Education Committee. 1957. 110 pp. 5s. Report on the two-day Conference held at Cheltenham in October 1957. Includes the six addresses with Discussions and list of delegates.

Proceedings of the Seventh Symposium in Applied Mathematics of the American Mathematical Society. Vol. VII. Applied Probability. American Mathematical Society. L. A. MacColl (*Editor*). McGraw-Hill. 1957. 104 pp. 39s. Nine papers presented at the Seventh Symposium for Applied Mathematics of the American Mathematical Society held in April 1955 at the Polytechnic Institute of Brooklyn. A different "theme" is chosen for each Symposium and this, on "Applied Probability," contained papers by Levy, Doob, Feller, Hopf, Münch, Batchelor, Kac, Llam and Koopman.

Three Steps to Victory. Sir Robert Watson-Watt. Odhams Press Ltd. 1958. 474 pp. Illustrated. 30s. *To be reviewed.*

Welding Handbook, Part I. Basic Principles and Data. American Welding Society. A. L. Phillips (*Editor*). 1957. 11 Chapters. Illustrated. 72s. The fourth edition of this well-known reference book is to be divided into five separate books, planned to appear every five years. This first book deals with basic principles and data.

Reports

AERODYNAMICS

Boundary Layer

Flow in the laminar boundary layer near separation. B. S. Stratford. R. & M. 3002. 1957.

A simple formula is derived for the separation of the laminar boundary layer. The method of derivation and a key test suggest that it should be reasonably accurate and of general application, including particularly the range of sharp pressure gradients and small pressure rises to separation. A partially new exact solution is found for the boundary-layer equations of motion; also the pressure distribution is obtained for continuously zero skin friction, this pressure distribution being expected to attain any given pressure rise in the shortest distance possible for a given laminar boundary layer provided that there is neither transition nor boundary layer control.—(1.1.4.1).

Theory of aerofoils on which occur bubbles of stationary air. L. C. Woods. R. & M. 3049. 1947.

Spoilers, split flaps and sometimes (with thin aerofoils) incidence alone cause the flow to separate from the aerofoil surface. This flow often re-attaches to form a closed bubble of virtually stationary air at a fairly constant pressure. A mathematical theory of the subsonic inviscid flow external to the bubble, whose position is assumed, is set out. The influence of the bubble on the lift and moment coefficients is calculated and some comments are made about the stalling of thin aerofoils.—(1.1.4.2 × 1.10.1.1).

Current tests on laminar boundary layer control by suction through perforations. S. F. J. Butler. R. & M. 3040. 1957.

To simplify the test procedure, most of the results were obtained using one or more closely spaced rows of perforations at a single chordwise station on an otherwise plain wing. A method is given, supported by some experimental evidence, for predicting the perforation spacing which would be required in a full-chord application from the results thus obtained at a single chordwise station.—(1.1.5.1).

Effects of probe tip geometry and size on measurements in a laminar boundary layer in supersonic flow. S. H. Galezowski. U.T.I.A. T.N. 17. *October* 1957.

A study of the effects of probe tip geometry and diameter on a laminar boundary layer was made by means of total and static pressure surveys. Five circular and one elliptical probe of tip width/tip height $w/h<1$, were investigated at a Mach number of 2·5.—(1.1.1.4 × 1.12.5).

An experimental study of the boundary layer behind a moving plane shock wave. W. A. Martin. U.T.I.A. 47. *May* 1957.

The shock tube boundary layer between the initial shock wave and the contact region was studied. Shadowgraph, Schlieren and interferogram photographs and thin film thermometer measurements indicated that the region was almost completely occupied by turbulent boundary layer. An interferometer study was made of this turbulent boundary layer for shock pressure ratios of 2·75 and 8. Experimental density profiles and boundary layer thickness measurements are given together with calculated temperature and velocity profiles, displacement and momentum thicknesses and local skin friction. Results are compared with the theory of Mirels in N.A.C.A. T.N. 3712.—(1.1.3.4).

Momentum transfer for flow over a flat plate with blowing. H. S. Mickley and R. S. Davis. N.A.C.A. T.N. 4017. *November* 1957.

The effect on the boundary layer of blowing air through a porous flat plate into a main airstream flowing parallel to the plate was studied experimentally. Measurements were made of velocity profiles and wall friction coefficients. Mainstream velocities ranging from 17 to 60 ft./sec. were used, the mainstream Euler number was zero, and a length Reynolds number variation of 4×10^4 to 3×10^6 was investigated.—(1.1.6.1).

Compressible Flow—*see also* Thermo-aerodynamics

A re-examination of the use of simple concepts for predicting the shape and location of detached shock waves. E. S. Love. N.A.C.A. T.N. 4170. *December* 1957.

The results show that simple concepts and modifications of existing methods can yield good predictions for many nose shapes and for a wide range of Mach numbers.—(1.2.3.2).

Control Surfaces—*see* Loads
Wings and Aerofoils

Fluid Dynamics

On the spectrum of natural oscillations of two-dimensional laminar flows. D. Grohne. N.A.C.A. T.M. 1417. *December* 1957.

If the stability of a laminar flow is investigated by the method of small oscillations, a complicated eigenvalue problem is encountered. So far, attention has been directed toward the isolation of those normal modes of oscillation which are either neutrally stable or which grow in time. Here the entire spectrum of characteristic values and the form taken by the associated oscillations are dealt with.—(1.4).

Internal Flow

An experimental investigation of the pressure recovery of a perforated-wall internal-compression intake at a free-stream Mach number of 2·5. *D. Brown. U.T.I.A. T.N.* 18. *May* 1957.

An axisymmetric internal compression intake of the reversed de Laval nozzle type (ideal or perfect diffuser) has been tested for total pressure recovery, at a free stream Mach number of 2·5 and a Reynolds number, based on intake diameter, of 5×10^5. The tests were conducted at zero angle of attack. To overcome the starting difficulty, wall perforation was used to bleed off the excess mass flow.—(1.5).

Loads—*see also* Wings and Aerofoils

Some effects of shed vortices on the flow fields around stabilizing tail surfaces. R. W. Stone and E. C. Polhamus. AGARD Report 108. *April-May* 1957.

A brief study is made of the effects of vortices shed primarily from bodies on the flow angularities in the regions of stabilising tail surfaces.—(1.6.3 × 1.8.1.2).

An analytical investigation of the gust-alleviating properties of a simple pitch damper. N. L. Crabill. N.A.C.A. T.N. 4173. *December* 1957.

The response to atmospheric gusts of a lightly damped aeroplane model flying at a Mach number of 0·7 at sea level has been studied analytically for a fixed elevator and for varying amounts of viscous restraint of a mass-overbalanced elevator.—(1.6.3 × 1.8.2.1 × 1.3.2).

Stability and Control—*see* Loads
Testing and Instruments

Thermo-aerodynamics

Effects of leading-edge blunting on the local heat transfer and pressure distributions over flat plates in supersonic flow. M. O. Creager. N.A.C.A. T.N. 4142. *December* 1957.

Surface pressures and heat transfer rates were measured on flat plates with various values of blunting for a Mach number of 4 and Reynolds numbers per in. of 2380 and 6600. A method was developed to correlate local Reynolds numbers from the present data with data from other sources covering a wide range of test conditions.—(1.9.1 × 1.2.3).

NOTE.—*The figures in parenthesis at the end of each Summary are for office use only.*

WINGS AND AEROFOILS—*see also* BOUNDARY LAYER
TESTING AND INSTRUMENTS

Investigation of deflectors as gust alleviators on a 0·09-scale model of the Bell X-5 airplane with various wing sweep angles from 20 to 60 at Mach numbers from 0·40 to 0·90. D. R. Croom and J. K. Huffman. N.A.C.A. T.N. 4175. *November* 1957.

An investigation has been made in the Langley high-speed 7 ft.× 10 ft. tunnel to determine the effectiveness of deflectors as gust alleviators on a 0·09 scale model of the Bell X-5 research aeroplane with wing sweep angles from 20° to 60°.—(1.10.2.2×1.3.4×1.6.3).

Investigation of the effects of propeller diameter on the ability of a flapped wing, with and without boundary layer control, to deflect a propeller slipstream downward for vertical take-off. K. P. Spreeman. N.A.C.A. T.N. 4181. *December* 1957. —(1.10.2.2×29).

TESTING AND INSTRUMENTS— *see also* BOUNDARY LAYER

Wind tunnel wall interference effects on oscillating aerofoils in subsonic flow. W. P. Jones. R. & M. 2943. 1957.

A theory is developed for estimating the effect of wind-tunnel walls on the air forces acting on an aerofoil oscillating in a subsonic airstream. The method is applied to calculate aerodynamic derivatives for an oscillating flat plate in a wind tunnel of height equal to 4·75 aerofoil chord and a Mach number of 0·7. Results obtained are tabulated for comparison with the known theoretical free-stream values.—(1.12.1.1×1.8.2.2).

Interference corrections for asymmetrically loaded wings in closed rectangular wind tunnels. H. C. Garner and W. E. A. Acum. R. & M. 2948. 1957.

The basic theory of wall interference in closed rectangular tunnels is outlined. The tunnel-induced upwash is expressed in terms of the loading on the wing and four quantities dependent on the shape of tunnel. These quantities are evaluated for a duplex tunnel and may be computed for a general rectangular shape. The correction to incidence, pitching moment, rolling moment, drag and yawing moment are discussed in detail and all the corrections are summarised and expressed as products of experimental aerodynamic coefficients and theoretically determined quantities. These are evaluated for an arrowhead wing with various ailerons in a duplex tunnel.—(1.12.1.2×1.10.1.2).

An experimental investigation of temperature and pressure recovery, running time and blockage characteristics of the U.T.I.A. 16 in. × 16 in. supersonic wind tunnel. J. B. Murray. U.T.I.A. T.N. 16. *August* 1957.

Tests have been conducted at a Mach number of 2·49 to investigate the effect of various cone model configurations on the pressure recovery in the sphere, running time and blockage area in the test section of the UTIA 16 in.× 16 in. supersonic blowdown wind tunnel. Further, the recovery temperature in the sphere was measured as a function of tunnel running time.—(1.12.1.3).

Tube wind tunnel. A special type of blowdown tunnel H. Ludwieg. AGARD Report 143. *July* 1957.

A short description of the tube wind tunnel is given. This is a special type of blowdown tunnel, the air container of which consists of a long cylindrical tube. The air in the tube is pre-accelerated by an expansion wave before entering the nozzle of the tube tunnel. In this way a good constancy of stagnation pressure and of stagnation temperature is reached without the use of any control valve and heat accumulator. The influence of the wall friction in the tube on the stagnation pressure and stagnation temperature in the test section is discussed. Experiments carried out in order to investigate this effect are reported, showing good agreement with the theoretical results. Means to reduce or to compensate the influence of the friction at the tube wall are dealt with. Possibilities for application of the tube tunnel are mentioned.—(1.12.1.3).

Experimental and theoretical study of mean boundary conditions at perforated and longitudinally slotted wind tunnel walls. C. F. Chen and J. W. Mears. ASTIA AD-144320. *December* 1957.

A mean boundary condition has been derived for the flow of an incompressible inviscid fluid along a longitudinally slotted wall taking into consideration the finite thickness of the slats. The flow was investigated near a wall along its longitudinal axis.—(1.12.1.2).

Development of a 400-*c.p.s. servo recorder. R. E. Klautsch. AEDC-TN*-57-47. *ASTIA AD*-144321. *December* 1957.

Measurement of wind tunnel test parameters becomes increasingly difficult as accuracy and resolution requirements are increased. In an effort to improve the existing methods of measuring the outputs of variable-resistance sensing elements under test conditions, a 400 c.p.s. null-balance servo-system was developed. A general description and a detailed explanation of various circuits used in this system is given, along with a discussion of certain developmental problems encountered.—(1.12.6).

A thermocouple subcarrier oscillator for telemetering temperatures from pilotless aircraft. C. L. Fricke. N.A.C.A. T.N. 4128. *December* 1957.

An oscillator is described which, in conjunction with the N.A.C.A. telemetering system, gives a satisfactory method for telemetering temperatures. The design uses a diode-bridge modulator in a phase-shift oscillator; the thermocouple voltage is changed to alternating current and used to shift the phase and hence to change the frequency of oscillation.—(1.12.6×13).

Measurement of static pressure on aircraft. W. Gracey. N.A.C.A. T.N. 4184. *November* 1957.

Existing data on the measurement of static pressure by means of static-pressure tubes and fuselage vents at subsonic, transonic, and supersonic speeds are presented. Static-pressure errors are given for isolated tubes and vents and for installations ahead of the fuselage nose, wing tip, and vertical tail fin, and on the fuselage. Various methods of calibrating installations in flight are briefly discussed.—(1.12.5×13).

AEROELASTICITY

An experimental and theoretical study of the effect of fuel on pitching-translation flutter. J. L. Sewall. N.A.C.A. T.N. 4166. *December* 1957.

Analytical flutter studies were made for 2 two-dimensional fuel-loaded wing models, and the results are compared with experimental results for bending-to-torsion frequency ratios near one. One of the models was made so that water, simulating fuel, could be carried internally in three compartments separated by sealed spanwise partitions. In the other model, fluid was carried externally in a pylon-mounted fuel tank without baffles. Good agreement between theory and experiment was obtained for both models. —(2).

DESIGN AND CONSTRUCTION

See AIRCRAFT OPERATION
AVIATION MEDICINE

AIRCRAFT OPERATION

A study of the aircraft arresting-hook bounce problem. J. Thomlinson. R. & M. 2980. 1957.

The kinematics of an arresting-hook unit are studied to determine, within the limits of the assumption of a perfectly rigid hook unit, the damper force necessary to control hook bounce. The necessity for a smooth deck and the desirability of small trail angle for the hook unit are demonstrated from several aspects. The design requirements for a hook damper unit are discussed in all their the up-swing motion of an arresting hook unit immediately following engagement of an arresting wire. The functional aspects and methods are given for determining behaviour of arresting wires after being depressed by the passage of aircraft wheels is also outlined.—(54.5.2).

The influence of drag characteristics on the choice of landing approach speeds. D. Lean and R. Eaton. AGARD Report 122. *May* 1957.

A study has been made of the lift-drag characteristics of 19 jet aircraft which have minimum comfortable approach air speeds that are fairly well established.—(5).

A classification system for unprepared landing areas. D. P. Samson. AGARD Report 129. *May* 1957.

A method of classifying any unprepared landing area is described under the main headings of (i) landing area, (ii) terrain configuration, (iii) surface roughness, and (iv) soil description and bearing capacity. This classification, with subdivisions, results in a numerical "terrain designator" and should assist when stating design requirements for new aircraft.—(5).

AVIATION MEDICINE

Some ground measurements of the forces applied by pilots to a side-located aircraft controller. R. F. Brissenden. N.A.C.A. T.N. 4171. *November* 1957.

Ground tests have been made to determine pilots' force capabilities on a proposed side-located aircraft controller. In addition to maximum force capabilities, pilots participating in the tests indicated forces that they considered desirable for operation of the controller. A neutral position and a range of deflections and forces are suggested.—(9×4.2.1).

FLIGHT TESTING

See AERODYNAMICS—TESTING AND INSTRUMENTS

INSTRUMENTS AND EQUIPMENT

Development of a lightweight distance-measuring interrogator. Part I. The model DIB interrogator. C. C. Trout and W. E. Haworth. CAA TDR 228. *December* 1956.

The development of a lightweight distance-measuring interrogator, Type DIB, for use in private and smaller commercial aircraft, is described. This equipment contains only 23 vacuum tubes and has an installed weight of less than 25 lb. The specification is included, along with a detailed description of the theory of operation of the equipment. Laboratory and flight tests are described, and the results in terms of performance and accuracy given.—(18.1).

Development of a lightweight distance-measuring interrogator. Part II. The model DIC interrogator. C. C. Trout. CAA TDR 292. *January* 1957.

The results of tests with the model DIC distance-measuring interrogators developed by the National Aeronautical Corporation are described. The model DIC interrogator provides continuous indication of distance from a selected ground station. It is composed of a receiver, distance indicator, transmitter, and associated distance-searching and -tracking circuits. Typical performance data for equipments developed under the contract are presented, along with the results of tests made to determine compliance with the development specifications.—(18.1).

MATERIALS

Cermets as potential materials for high-temperature service. O. A. Sandven. AGARD Report 99. *April* 1957.

The chemical, physical and mechanical properties of the most important and promising Hard Metals and Cermet systems, are reviewed, with special attention to the creep resistance and ductility. Some experimental results on the system NbC-TiC Ni are reported.—(21.2.2).

A survey of the structural properties of some high strength sheet steels. M. A. Melcon. AGARD Report 101. *April* 1957.

Steels which are specifically covered are 420, 422, 422M, AM350 and 17-7PH. Mechanical properties at room and elevated temperature are summarised. Stress-strain curves in tension and compression are presented at room and elevated temperature. Heat treatment, corrosion resistance, and formability of the various alloys are discussed. Some fatigue, creep, and stress-rupture data are presented. Tear strength is evaluated for some of the materials. Fabrication problems are also covered.—(21.2.1).

Sintered aluminium S.A.P. F. Bollenrath. AGARD Report 103. *April* 1957.

A new material made by compressing, sintering, and extruding aluminium powder is described. This material is called S.A.P. (Sintered Aluminium Powder) and has been developed by Aluminium Industrie A.G., Neuhausen, Switzerland. Outstanding mechanical properties at elevated temperatures are claimed.—(21.2.2).

Effect of overheating on creep-rupture properties of S-816 alloy at 1500°*F. J. P. Rowe and J. W. Freeman. N.A.C.A. T.N.* 4081. *December* 1957.

The effects of overheating were evaluated in terms of the changes in creep-rupture characteristics at 1500°F of S-816 alloy under stresses within the range of rupture strengths of the alloy for 100 to 1,000 hours. Overheat periods were predominantly of 2 minute duration and were applied cyclically at approximately 5 or 12 hour intervals. The possible damage from overheating was believed to include internal metal structure changes induced by exposure to the higher temperatures and loss of life by creep if stress was present during the overheats.—(21.2.2).

Abnormal grain growth in nickel-base heat-resistant alloys. R. F. Decker et al. N.A.C.A. T.N. 4082. *December* 1957.

Controlled laboratory experiments were carried out on samples of bar stock of air- and vacuum-melted Waspaloy, Inconel X-550, and Nimonic 80A alloys to find conditions of heating and hot-working which resulted in abnormal grain growth. These experiments were mainly limited to normal conditions of heating for hot-working and for heat treatment.—(21.2.2).

Effect of overheating on creep-rupture properties of HS-31 alloy at 1500°*F. J. P. Rowe and J. W. Freeman. N.A.C.A. T.N.* 4083. *December* 1957.

The effects of overheating were evaluated in terms of the changes in creep-rupture characteristics at 1,500°F of HS-31 alloy under stresses within the range of rupture strengths of the alloy for about 100 to 700 hours. Overheat pediods were predominantly of 2 minute duration and were applied cyclically at approximately 5 or 12 hour intervals. The possible damage from overheating was believed to include internal metal structure changes induced by exposure to the higher temperatures and loss of life by creep if stress was present during the overheats.—(21.2.2).

Abnormal grain growth in M-252 and S-816 alloys. R. F. Decker et al. N.A.C.A. T.N. 4084. *November* 1957.

An experimental investigation was carried out on air- and vacuum-melted M-252 and S-816 alloys to find conditions of heating and hot-working which resulted in abnormal grain growth. The experiments were mainly limited to normal conditions of heating for hot-working and heat treatment, and normal temperatures of solution treatment were used to allow grain growth after susceptibility to abnormal grain growth was developed by various experimental conditions.—(21.2.2).

Investigation of the compressive strength and creep of 7075-T6 aluminum-alloy plates at elevated temperatures. W. D. Deveikis. N.A.C.A. T.N. 4111. *November* 1957.

Elevated-temperature compressive strength test results from room temperature to 600°F and creep test results from 350°F to 500°F are presented for V-groove edge-supported plates of 7075-T6 aluminium alloy. The test results are analysed to verify procedures for estimating maximum strength from material stress-strain curves and creep-failure stresses from isochronous stress-strain curves. The results are also compared with similar results for 2024-T3 aluminium alloy plates.—(21.2.2).

PROPELLERS

See AERODYNAMICS—WINGS AND AEROFOILS

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